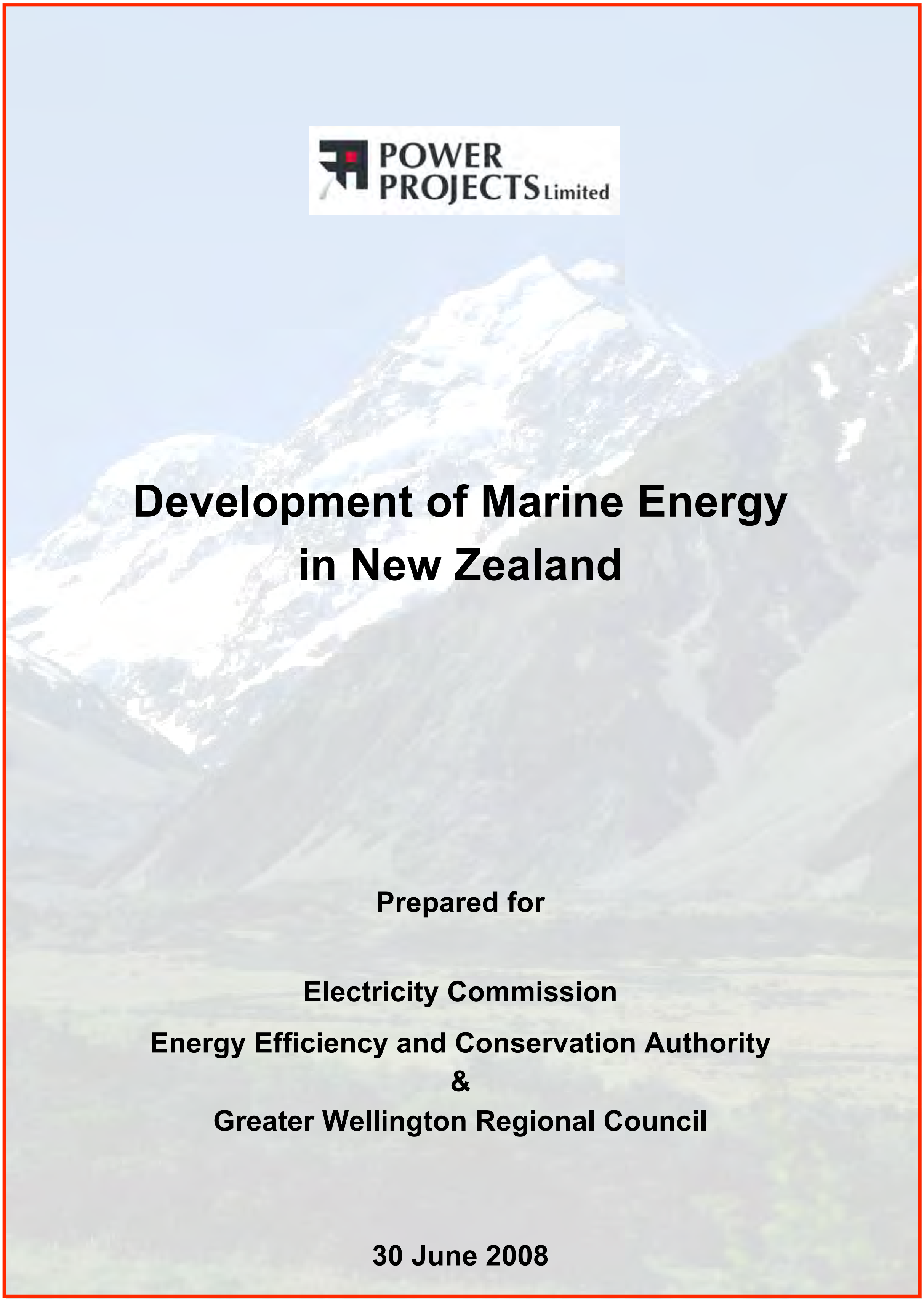


Development of Marine Energy in New Zealand

Prepared for

Electricity Commission
Energy Efficiency and Conservation Authority
&
Greater Wellington Regional Council

30 June 2008

CONTENTS

APPENDICES

FIGURES

TABLES

Disclaimer

POWER PROJECTS Limited (hereinafter referred to as the "Consultant") warrants that any estimates, opinions, conclusions or recommendations presented in this report are reasonably held or made as at the time provided. The recipient accepts and acknowledges however, that neither the Consultant nor its advisors, agents, officers or employees make any representation or warranty as to the accuracy or reliability of any estimates, opinions, conclusions, recommendations (any or all of which may change without notice) or other information which has been provided and, to the maximum extent permitted by law, the Consultant disclaims all liability and responsibility for any direct or indirect loss or damage which may be suffered by any recipient through relying on or use of any estimates, opinions, conclusions, recommendations or other information provided by the Consultant.

Executive Summary

The Electricity Commission (EC), Energy Efficiency and Conservation Authority (EECA) and Greater Wellington Regional Council (GWRC) want to address the potential development of marine energy generation in New Zealand. This study reviews the current state of domestic and international marine energy technologies and their development and deployment. New wave and tidal/ocean current energy resource assessments have been undertaken by integrating new mapping of the resources with the performance characteristics of modelled wave and tidal/ocean current devices to derive the potential electricity generation from device arrays at promising sites.

The pace of domestic marine energy activity has picked up since 2006 with the deployment of the first experimental wave energy converter (WET-NZ device), the grant of the first consents for an in-stream tidal prototype (Neptune Power) and the award of $1.85 million from the Marine Energy Deployment Fund (MEDF) to Crest Energy for its proposed tidal stream project in Kaipara Harbour, subject to grant of a resource consent for the project.

The pace of international marine energy precedes domestic developments. Verdant Power has installed and operated six 35 kW tidal turbines in the East River of New York since 2007. Ocean Power Technologies has had a 40 kW PowerBuoy working continuously off the New Jersey coast for over 2 years now. More recently, the first full-scale tidal stream demonstrator, the Marine Current Turbines' SeaGen device was deployed in Strangford Lough, Northern Ireland, in April 2008. Pelamis Wave Power is now forecasting that its long-awaited Pelamis deployment of 3 Pelamis devices at Aguçadoura, off Portugal, will occur in the third quarter of 2008.

To assess the potential for marine energy in New Zealand four tasks have been carried out in the analysis reported here:

1. All marine energy technologies have been reviewed with a focus on devices, which may have particular application in New Zealand waters. Wave and tidal/ocean current devices have the best potential.
2. Factors that affect the pace of development and uptake of marine energy technologies, including Government initiatives, industry activity and investor interest have been reviewed.
3. Marine energy resources and reserves have been calculated by devising power spectra for three generic wave devices and two generic tidal/ocean current devices. These spectra have been applied to an extensive modelling study of the national and wave and tidal/ocean current resources to define areas of interest. Nominal arrays of both wave and tidal/ocean current devices have then been modelled to determine the capacity (in MWs) and annual electricity production (in GWh/year) for six wave sites around the country and six tidal sites in two locations.
4. A case study has been undertaken on the Wellington Coastal Marine Area, where national-scale modelling indicates excellent tidal and potential wave sites. A review of the potential constraints on a marine energy project in the Wellington CMA complements the wave and tidal resource assessments.

Of all the marine energy sources, wave and tidal/ocean current energy have the best potential for providing power to New Zealand in the future. Wave devices seek to harness either breaking waves or open-ocean swells, whilst tidal devices extract energy from either tidal rise and fall or tidal currents. Ocean thermal energy, osmotic power and marine biomass may have future potential but technologies to harness these energy sources are at an early stage of development. The potential for offshore wind is beyond the scope of this study.

Many wave device designs are under development and there is, as yet, no convergence on a common design. Five generic designs are maturing and are reviewed here. Two of these – attenuator devices (like the well-known Pelamis device) and point absorber devices (like the WET-NZ device) have been evaluated for their potential use at six New Zealand sites.

Whilst there are many different tidal device designs, the fastest to mature is probably the horizontal axis turbine – like a submarine wind turbine. Tidal rise and fall technologies are simple – barrages or impoundments – but there are very few sites where such technologies could be deployed in New Zealand. Two different but related generic horizontal axis turbines have been analyzed in this study.

The development of marine energy depends not only upon the ingenuity and capabilities of device developers but also upon an array of external factors, including national targets for uptake of renewables (including marine), government assistance, funding mechanisms, industry developments and investor confidence. The New Zealand Government has begun to support marine energy but specific support for new renewables is limited. Policy instruments, such as renewables obligations, feed-in tariffs and regulatory assistance, have stimulated marine energy device developments and deployments in the United Kingdom, Portugal, Denmark, Canada and the United States.

The international and national growth of wind energy has been reviewed as a template for the potential growth of marine energy. Current development of marine energy is lagging behind forecasts of only 7 – 8 years ago. However, developers with maturing technologies are beginning to permit multiple sites so very rapid growth may occur, as new technologies mature to commercial status. Two domestic marine energy developers have announced aggressive development plans, which are at odds with the observed development of the wind industry here. Although New Zealand will see the first demonstration projects in the next 3 – 5 years and the first commercial deployment in 3 – 7 years.

The Wellington Coastal Marine Area (CMA) has been the subject of a detailed case study, which shows that it has exceptional tidal/ocean current resources but limited wave resources (as confirmed by the site modelled off the Wairarapa coast). The policy environment in the Wellington CMA is described and the terms of the Neptune Power consent are instructive for future developments. Environmental considerations and competing uses, such as fishing and navigation, will need to be considered by project developers and there is an absence of useful data, such as marine mammal interactions with marine energy devices, whale migration routes and shipping movements. Further work will be required to measure and map these issues and to address and other environmental issues.

In summary, mapping and modelling undertaken in this study indicates that marine energy can make a significant contribution to New Zealand's future electricity supply. Over 7,000 MW of wave energy reserves may be available, sites are abundant and geographically dispersed. The potential for tidal/ocean current energy is smaller (<1,000 MW) but some specific sites with real potential have been identified, noting also that harbours and inland passages were not mapped and modelled in this study. Site selection is critical and more detailed mapping will be required to identify sites of interest. Device selection and micro-siting of individual devices will also be critical for optimizing power production from device arrays at favourable locations. Such work is beyond the scope of this study but will be required to ensure that New Zealand and project developers make optimal decisions about marine energy investments.

PART 1: DEVELOPMENT OF MARINE ENERGY IN NEW ZEALAND

1.1 INTRODUCTION AND PURPOSE OF STUDY

The Electricity Commission (EC), is seeking advice on the potential development of marine energy generation in New Zealand to assist with planning for future transmission and generation investments. The Modelling Team has requested a report comprising three parts:

1. Review of current marine energy technologies both overseas and in New Zealand.
2. A timetable for the maturing technologies to penetrate the New Zealand generation market.
3. A short list of potential marine energy schemes, including location, timeframe, capital cost estimates, installed capacity (MW) and electricity production (GWh).

No study of this kind has been undertaken in New Zealand before. Although recent and current work has focussed on evaluating the potential of New Zealand's wave and tidal stream resources, there have been no published attempts to assess potential schemes or to calculate an actual national contribution by marine energy to the future generation portfolio.

The domestic marine energy sector is a very dynamic one. During the course of the research for this report, five key events have occurred:

1. The first resource consent for a tidal stream prototype project was granted (10 April 2008; Section 6.2.3).
2. Consent hearings for resource consents for a utility-scale tidal stream project were held (26 - 30 May 2008; Section 6.2.2).
3. The first award under the Marine Energy Deployment Fund (MEDF) was made (29 May 2008; Section 3.3.1)
4. The second round of funding under the MEDF was foreshadowed (as above)
5. The first wave device prototype was deployed in Wellington Harbour (5 June 2008; Section 6.2.5).

Beyond these projects, however, there has been very little public information released by other device/project developers. Thus any review of the contribution and timetable for development of national resources must be speculative. However, this proposal is aimed at extending knowledge of the national marine energy potential by going beyond resource evaluations. Coupling national and regional modelling of wave and tidal-stream resources with the potential energy production from three example devices, in analysis of some site-specific deployments, will enable extrapolation of regional and national deployments.

The Commission has recently commissioned other organizations to undertake similar studies in wind and hydro projects and conducted similar work internally on geothermal developments. However, in all three cases, mature wind, hydro and geothermal technologies and well-researched resources have led to publicly available listings of potential generation projects. The scope for the work reported here did not allow the development of a rank-ordered listing of potential marine energy project developments, ranked by their unit cost of electricity. The aim is to approximate the development of marine energy by the evaluation of potential site-specific wave and tidal-stream projects and extrapolate these projects to the regional and national scales.

1.2 LAYOUT OF THE REPORT

This report is laid out in six parts. Following this introduction, the contents of the following parts are as follows:

Part 2 This part is a review of the development status of wave and tidal stream energy converter devices both in New Zealand and overseas. The focus is on the current status of devices, their performance characteristics, where such data are available and projects in which they are being deployed. The review discusses generic marine energy converters and gives examples of the most mature technologies, *i.e.,* those that have already been deployed, at least, at prototype level.

Part 3 This part sets out the issues affecting the timing of development of current technologies and their deployment in New Zealand. These include government targets and forecasts, whether mandatory or aspirational, developers' commercialization strategies, funding and regulatory mechanisms and industry developments.

Part 4 This part is a review of the wave and tidal/ocean current energy resource assessments. It describes the resource modelling undertaken in this study in the layperson's terminology, although those interested in the technical details of the modelling will want to read the two Appendices B & C on wave modelling and MetOcean Solutions' report.

Part 5 Drawing on the three previous parts, the results of modelling some specific areas for potential wave and tidal/ocean current are described in detail. Modelling involved the application of the generic devices (based on real examples) to the resource forecasts derived for each area. Five wave and one tidal/ocean current areas have been evaluated.

Part 6 International forecasts for the development of the international marine energy industry have been made by a number of overseas organizations. These forecasts are compared with the demonstrated growth of the international wind industry. Within New Zealand six projects, which have been publicized, are discussed here. This section ends with a forecast for the uptake of marine energy in New Zealand.

Part 7 This part presents the results of the evaluation of the wave and tidal/ocean current potential of the Wellington Coastal Marine Area. This is followed by a review of the constraints on any potential marine energy projects in the Wellington CMA. The constraints include operative policies and regulations, existing marine energy projects, submarine cables, marine reserves and conservation areas, fishing, navigation and other exclusions. This part serves as a case study for project developers, not only in the Wellington CMA but nationally, acknowledging that constraints faced by marine energy project developers will differ from site to site.

Declaration of Interest

Power Projects Limited is a co-founder and current participant in the Wave Energy Technology – New Zealand (WET-NZ) R & D programme. This is a consortium R & D programme with Industrial Research Limited and the National Institute of Water and Atmospheric Research. Over the last four years the consortium has developed a point absorber device, which has been deployed in Pegasus Bay off Christchurch and, more recently, Evans Bay in Wellington harbour. Power Projects Limited has used only what information has been released in the public domain to describe the WET-NZ programme in this report. See Section 6.2.5 for more detail about the programme.

PART 2: MARINE ENERGY TECHNOLOGIES

2.1 MARINE ENERGY SOURCES

There are a number of different potential ways of extracting energy from the oceans. None has yet achieved the status of commercial viability internationally, although most have been under consideration and development since the oil price shocks of the 1970s. Not all of these potential energy sources will have application in New Zealand, because resource and environmental issues will have an impact.

There are seven principal marine sources, from which energy could be extracted. Internationally, all of these sources are currently being investigated to differing degrees but technologies – at various stages – are being developed to harness them (Table 2.1). By far the biggest international investments are going into developing conversion technologies for wave and tidal stream energy, although planning pressure is driving increasing consideration of offshore wind in North European Atlantic coast settings.

Energy Source	Conversion Technology	Products
Waves		Electricity Hydrogen Biofuels Heat Potable water (& combinations of above)
Open ocean swells	Point absorbers; Attenuators	
Breaking waves	Oscillating water columns (OWCs); Overtopping devices	
Tides		
Tidal rise and fall	Barrages; Impoundments	
Tidal/ocean currents	Turbines; Reciprocating devices	
Heat	Ocean Thermal Energy Conversion (OTEC)	
Osmotic power	Reverse osmosis	
Marine biomass	Farming and harvesting	
Offshore winds	Offshore wind turbines	

Table 2.1: Marine Energy Sources and Products

2.1.1 Wave Energy

Wave energy can be separated into two potential extractable sources: open ocean swells and breaking waves. Open ocean swells result from the aggregated effects of wind currents blowing across the surface of the ocean, particularly in major storms. Swells result from the constructive interference of waves resolving into larger waves with bigger amplitudes (*i.e.,* wave height) and longer wavelengths (*i.e.,* longer periods between wave peaks). Breaking waves result from the incidence of these ocean swells on the seabed, as waves approach the coast.

Anyone flying into Wellington airport from the south will have noticed the '*herringbone*' patterns created by two or more swell directions in the open sea some kilometres south of the airport. As the swells approach the coast they suffer friction with the shallowing ocean bottom, which causes the swells to rotate into a single direction roughly parallel with the coast. With increasing shallowness, wave heights increase and increasing friction causes the waves to topple over, finally breaking on the beach.

Devices, which extract energy from waves, are called '*oscillating water column'* devices (OWCs) or '*overtopping*' devices (see Sections 2.2.3 and 2.2.4). Both are sometimes lumped together as ‘*termina*tor’ devices. Devices, which extract energy from open ocean swells, are classified as either ‘*attenuator*’ devices or ‘*point absorber*’ devices (see Sections 2.2.6 and 2.2.7).

2.1.2 Tidal Energy

Like wave energy, tidal energy can be split into two basic forms: tidal rise and fall and the resultant tidal stream or ocean currents arising from that rise and fall and modifications by weather conditions. Tidal rise and fall is controlled by the relative position and gravitational attraction of the moon and, to a lesser extent, the sun on the world’s oceans. The tides follow a diurnal cycle slightly longer than a normal day, and a seasonal cycle, which gives rise to neep and spring tides. Tidal currents arise to accommodate the diurnal rise and fall, although local weather effects and local seabed topography can modify them. Whilst the astronomical control on tidal rise and fall enables an extended forecast of high and low tides, this certainty does not extend to tidal stream currents because of the weather effects. For example there are diurnal tidal effects in Cook Strait, which can be forecast, *i.e.,* tide tables. However, resultant currents can be severely affected by local weather conditions to the extent that, in severe storm conditions, the tide does not ‘*turn*’, as would be expected (Stevens *et al.,* 2006).

Conversion technologies, which can harness electricity from tidal rise and fall and from tidal currents, are quite different. There are two basic tidal rise and fall technologies, although their conceptual operation is similar. These are tidal barrages and tidal impoundments. Tidal barrages are essentially barriers across rivers, estuaries or bays, which disrupt the normal tidal rise and fall, holding back the rising or falling water such that water level on one side of the barrier or impoundment is out of synchronization with the water level on the other side. As the point of maximum difference is reached the barrage or impoundment mechanism is opened, allowing flow across it. The flowing water is used to generate electricity and can be utilized on both the ebb and the flood tide.

Tidal barrages are an ancient technology. There is evidence of small tidal barrages being used to generate rotary motion for corn grinding in post-Roman times and the oldest tidal-powered corn mill (Eling Mill near Southampton) has been continuously operational since the 9th Century.

The only modern era marine energy device of any scale is the Rance River barrage on the estuary of that river near St. Malo in northern France. This barrage became operational in 1967 and has a generation capacity of 240 MW. Originally it only operated on the ebb tide but was converted to both ebb- and flood tide operation in 1997. There are two other smaller working examples at Annapolis Royal (20 MW) in Nova Scotia and Kislaya (0.4 MW), near Murmansk, Russia.

2.1.3 Heat (Ocean Thermal Energy Conversion)

The thermal energy of ocean water can be converted into electrical energy by a process called ocean thermal energy conversion (OTEC). OTEC is based upon heat exchange between deep ocean water, pumped to the surface, and warm shallow or surface water. The process requires a significant heat difference between these two sources of water. Such differences occur in tropical latitudes either side of the Equator, somewhat distorted by major ocean currents such as the Gulf Stream. However, outside the Tropics the temperature difference is too small to enable sufficient electricity to be produced economically from the heat exchange process.

OTEC projects have been trialled in Hawaii and a 30 kW device OTEC plant is being tested in Japan. Mexico is considering the installation of some large-scale OTEC plants to produce both electricity and potable water. OTEC installations are unlikely to be economic in New Zealand and are not considered further in this report.

2.1.4 Osmotic Power

Energy can be extracted from ocean water through the salinity difference (or gradient) between salty seawater and freshwater. Statkraft, the Norwegian electricity transmission grid operator and utility, has recently embarked on a research project to build the world's first osmotic power device (Statkraft, 2006). The prototype develops only 35 kW, so commercial development of osmotic power is probably a considerable time from commercial development. Osmotic power is not a commercial prospect for New Zealand at present or in the mid-term future.

2.1.5 Marine Biomass

Early interest in marine biomass was demonstrated in the 1970s by proposals to '*farm*' kelp on the Pacific coast and to harvest and process it to produce oil. The concept was researched but no trials were conducted and commercial development did not proceed. Since then other marine biomass projects have been or are now under consideration, including the harvesting and processing of marine algae to produce bio-fuels. Such projects could be attractive to New Zealand because of its very large Exclusive Economic Zone (potentially the 4th largest in the world).

Marine biomass would provide a fuel, most likely restricted to transport applications. It is unlikely that it would be economic to produce the bio-fuel, only to further convert it to electricity for wider uses. For this reason and for the very early stage of development, marine biomass is not considered further in this report.

2.1.6 Offshore Winds

In European Atlantic and North Sea coast countries, offshore wind farms have been developed since 1991 (Vindeby, Denmark) and the United Kingdom (Blyth Harbour, 2003). Currently the largest offshore wind farm is Horns Rev off the north coast of Denmark (80 x 2 MW Vestas V-80 turbines), although a 341-turbine array, called the London Array, is under construction in the North Sea, roughly 70 km ENE of London. The London Array will eventually have the same capacity as the Huntly Power station, *i.e.,* 1,000 MW. However, a slightly larger project has already been proposed off the North Devon coast. If built, the Atlantic Array will have 350 turbines with a generation capacity of 1,500 MW (providing power to over 1 million homes).

Most offshore wind projects are based upon effectively adapting onshore wind turbine generators for offshore use and developments are limited to shallow water applications. The drivers for offshore applications are better wind resources (smoother flows with less damaging turbulence), decreasing onshore space for projects and, perhaps most importantly, reduced difficulty in planning consents caused by local opposition.

New Zealand has not yet reached the capacity of its onshore wind opportunities – as indicated by the nearly 4,000 MW of onshore wind projects that have been built (322 MW by end-2007) or proposed to date. However, opposition to onshore wind farms has grown and consenting is becoming more difficult and costly. Unfortunately, New Zealand's coastline does not shelve like the North Sea coast and any future offshore wind projects in New Zealand may have to be close to shore, somewhat negating the benefits of offshore sites. It is worth noting, however, R & D is under way on floating wind turbine generators, which, if successful, would free New Zealand developers to locate their arrays further offshore (Economist Technology Quarterly, 7 June 2008).

2.1.7 Products of Marine Energy

A range of potential products can be produced using marine energy generation, including electricity, hydrogen (by on-site electrolysis), heat, bio-fuels (of various types) and potable water (Table 2.1). The vast majority of devices are being designed with electricity as the intended end product. Some devices, such as the Australian CETO will deliver both electricity and potable water, whilst Oceanlinx is intending to build both electricity-producing and water-producing designs, following its successful prototype deployment at Port Kembla, south of Sydney.

2.2 WAVE ENERGY DEVICES

2.2.1 Classification

Although fewer than tidal stream devices, an impressive number of wave energy design concepts is currently under development. The European Marine Energy Centre currently lists 51 wave energy device developments (EMEC, 2008). Even this number is probably an under-estimate, as the authors of this report are aware of devices not listed in the compilation. Despite the number of wave energy devices that have been proposed, there is no commonly agreed standard classification. The classification listed below breaks devices down on three criteria:

1. Environmental location of the device,
2. Intended operational water depth, and
3. Physical construction or energy extraction methodology (Table 2.2).

Other classifications are possible. For instance, oscillating water column and overtopping devices are sometimes called '*terminator*' devices, because they resist the waves to absorb energy, whilst attenuator and point absorber devices can be classified as '*compliant*' devices.

Location	Water Depth (m)	Classification	Manufacturer	Device
Onshore	0	Oscillating Water Column		PICO plant, Azores
		Overtopping		Tapchan, Norway
Nearshore	1 - ~25	Oscillating Water Column	Oceanlinx	Oceanlinx
		Surge devices	Aquamarine	Oyster
		Overtopping/ terminator	Wavedragon	Wavedragon
Offshore	~25+	Attenuator	Pelamis WavePower	Pelamis
		Attenuator	C-Wave	C-Wave
		Attenuator	Raft designs	Martifer
		Point Absorber	Ocean Power Technologies	PowerBuoy
		Point Absorber	AWS II	AWS II
		Point Absorber	Finavera Renewables	AquaBuOY
		Point Absorber	Wavebob	Wavebob
		Point Absorber	Carnegie Corp.	CETO II
		Point Absorber	WET-NZ	"WaveWobbler"

Table 2.2: Simplified Classification of Wave Energy Converters

Note that the listing of devices in the previous table indicates that the devices are in active development. It is clearly not an exhaustive listing, nor is it intended that they devices listed are representative, other than of their generic classes.

2.2.2 Energy Distribution in Waves

Energy in waves takes two forms: potential energy and kinetic energy. Kinetic energy is the physical energy created by the position of the water mass, relative to the energy collector. Potential energy is due to gravity and its extraction involves the movement of the water from a higher to a lower potential energy position, usually converting the potential into mechanical energy in the process. The most obvious form of potential energy is the extraction of energy from the rising and falling of passing waves (Figure 2.1).

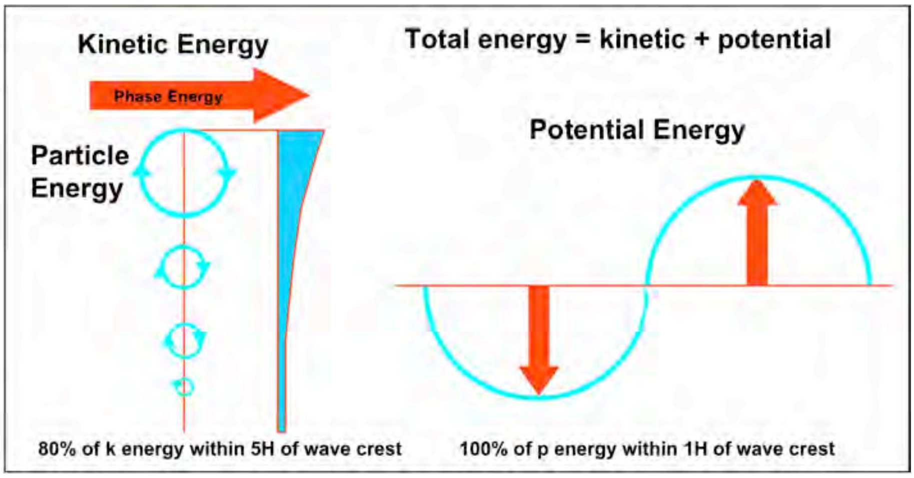


Figure 2.1: Energy Distribution in Waves

Kinetic energy is the energy produced by movement. Although waves appear to have a linear unidirectional movement, the particle motion in waves is approximately circular – the waves are notionally rotating cylinders moving to the shore. This circular motion is the reason why breaking waves at the beach appear to push and pull, as much as lift and drop, swimmers in the surf. Extraction of kinetic wave energy is achieved by using devices, such as turbines, which partially – but not completely – resist the circular wave motion. Surfers hitting the perfect wave are extracting both kinetic and potential energy on their graceful journeys to the beach.

The energy contained in waves can be resolved into three motion vectors:

1. Heave – the vertical component of motion
2. Surge – the horizontal component of motion
3. Pitch – the rotational component of motion

Wave energy converter designs are based upon extracting energy from one or more of these components of motion. Some devices are designed to extract energy from one particular vector, *e.g.,* heave or surge, whilst others seek to extract energy from a combination of these vectors.

Wave/swell environments are extremely complex, since a sea state is composed of local and immediate wind-sea interactions, old-wind seas generated some hours ago and long period swells from distant storms of several days. All of these may arrive from different directions and lead to very complex sea-states. Extracting energy from this complex sea-state, incident on a wave energy converter, is thus a complex problem.

In the following sections, devices are described in their respective environmental position, *i.e.,* relative to the coastline: onshore – nearshore – offshore.

2.2.3 Oscillating Water Column Devices

The structure of an oscillating water column device (OWC) is a fixed volume chamber, open below the water surface but closed above, except for a single outlet. The chamber is located either on the beach (or cliff) or nearshore, where waves are breaking. The basic operational principle is that the breaking wave causes a rise of water level within the chamber, which compresses the air above the water surface and forces it out of the single outlet and, in so doing, turns a turbine. As the wave recedes, the water level in the chamber drops and air is sucked back into the chamber. With the right configuration the turbine will continue to rotate. Energy is thus extracted from both rising and falling waves.

The first OWC device was the Pico Plant in the Azores, which was first commissioned in 1973. It suffered frequent operational problems and was abandoned during the 1990s. The plant has been significantly refurbished since 2000, although operation is still discontinuous (Neumann *et al.,* 2007).

Two other devices, Wavegen's LIMPET device and Australian Oceanlinx device (formerly Energetech) are both OWC devices, which have been discontinuously operational since 2000. The key differences between the devices are that firstly, Wavegen's LIMPET is coast-attached (Figure 2.2), whilst the Oceanlinx device is Figure 2.3).

Figure 2.2: The LIMPET OWC Device on Islay, West Coast of Scotland

Secondly, LIMPET uses a fixed blade turbine, called a Wells Turbine, which rotates in the same direction, regardless of the direction of the air current, whilst the Oceanlinx turbine establishes the unidirectional turbine rotation by rapidly variable pitch blades, which change direction as the air direction changes.

Figure 2.3: Oceanlinx Prototype under Test at Port Kembla, NSW, Australia

2.2.4 Overtopping Devices

Overtopping devices are relatively simple devices, based upon a low-head hydro design. Water from advancing waves is captured in a reservoir slightly above sea level, held and returned to the sea through conventional low-head hydro turbines, which generate power.

The earliest overtopping device was a tapered channel (Tapchan) excavated into cliffs in Norway. Breaking waves accelerated up the tapered channel and slopped over into a lower reservoir before being fed back to the sea. More recently, a couple of nearshore, bottom-sitting Danish devices, called WavePlane and Wave Dragon, have been proposed and are under development. Wave Dragon has had a measure of success and full-scale deployments are planned (Figure 2.4).

Figure 2.4: ~1/4-scale Wave Dragon in Nissum Bredning, Denmark

2.2.5 Surge Devices

Surge devices generally sit on the seabed in a nearshore setting and extract energy from the surging of passing waves (surge is the horizontal component of the wave motion). Surge devices consist of a base, which sits or is anchored to the shallow seabed, to which is attached by a hinge mechanism an arm or a baffle, which pivots in response to the surging movement of passing waves. There are at least three such devices under development, including Oyster (Figure 2.5), WaveRoller and BioWave. Development of a fourth surge device, EB Frond is currently on hold.

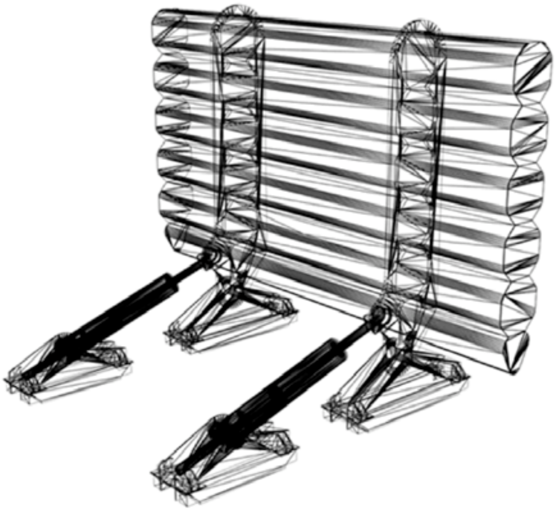


Figure 2.5: Aquamarine's Oyster Surge Device Design

A variant of this surging design is a pressure-sensitive device, which reacts to pressure changes of passing waves, rather than kinetic movement. The prototype design of the CETO device was a pressure-sensitive design but this device has been redeveloped as a more conventional point absorber design (Section 2.2.7).

2.2.6 Attenuator Devices

An attenuator device is essentially a floating device, which works in parallel to the wave movement direction and effectively rides the crests and troughs of swell waves. Movement along the length of the device can be controlled to produce energy. They are probably the most common device design. Because the devices have to span the wavelength (*i.e.,* the distance between two swell crests), they are usually very large (Figure 2.6).

Since the cross-sectional area of the device orthogonal to the swell crests is relatively small, the device experiences lower forces than a terminator device (such as an OWC or overtopping device). Attenuator devices can look markedly different but their basic principle of energy extraction is the same. The most well known attenuator device is Pelamis, the P750 prototype version of which is shown in the figure below. Three of these devices have been sold to a Portuguese utility, Enersis, and are in the process of being deployed at a site of the Portuguese coast, called Aguçadoura. The deployment was due in 2006 but has been delayed due to problems, reportedly with the device mooring system. Pelamis Wave Power is also constructing devices for Scottish Power Renewables for a deployment of 4 x 750 kW devices at the European Marine Energy Centre (the Orcadian Wave Farm) and a further deployment of up to 7 x 750 kW devices at the proposed Wave Hub facility in Cornwall (the West Wave project).

Figure 2.6: The Pelamis P750 Prototype in Leith, Edinburgh (workers show scale)

A power spectrum published by the developer of this device has been used in the resource modelling (Section 4.2.1).

There are also a number of different floating '*raft*' designs undergoing testing, *e.g.,* the Portuguese Martifer raft. However, development of raft designs has slowed relative to other design concepts.

2.2.7 Point Absorber Devices

Perhaps the second most common generic device design – after the attenuator devices – are point absorbers. Point absorbers have a physical analogy to conventional maritime navigation buoys. They are usually largely submerged, axi-symmetric and anchored to the seabed.

Point absorbers essentially have two key parts – a large spar, which either sits on the seabed or floats in the water column below the level of wave particle motion and a surface or near-surface float, which reacts to passing wave crests and troughs. As such point absorbers extract the heave component (*i.e.,* the vertical motion) of wave kinetic energy, although newer devices are being built which strive to extract energy from all three modes – heave, surge and pitch).

The devices have a small cross-section relative to an advancing wave front and thus do not extract as high a proportion of the passing energy as attenuator or terminator devices. However, their relative small areal footprint lends them particularly well to deployment in arrays and, as we shall see, most developers plan that individual devices will have low unit generation capacities (100 kW to 1 MW) but achieve utility scale by deployment in arrays. A high proportion of current academic research on point absorbers is dedicated to establishing array designs.

The most developed point absorber is the PowerBuoy developed by a New Jersey company, Ocean Power Technologies (OPT). Early versions of this device have been deployed since 1994 and the company is now involved in a number of deployment projects. The company was listed on the Alternative Investment Market of the London Stock Exchange (AIM) and, more recently, listed on the NASDAQ in 2007.

The PowerBuoy device is fairly representative of the generic concept of point absorber device geometry – a central axi-symmetric spar with a separate float (Figure 2.7).

Figure 2.7: 40 kW PowerBuoy Ready for Deployment

Another device currently under development is the Irish WaveBob device. This device has been trialled at the Galway Bay wave testing centre over the last two years and the company has recently opened an office in the United States as it looks to expand operations there. Again the WaveBob device comprises a central spar linked, in this case, by hydraulic arms to a separate float (Figure 2.8). Wavebob differs from the PowerBuoy in that the former is an entirely floating device, slack-moored to the seabed, whilst the PowerBuoy has a central spar, which rests on the seabed. The device has been significantly modified suffering damage in 2007.

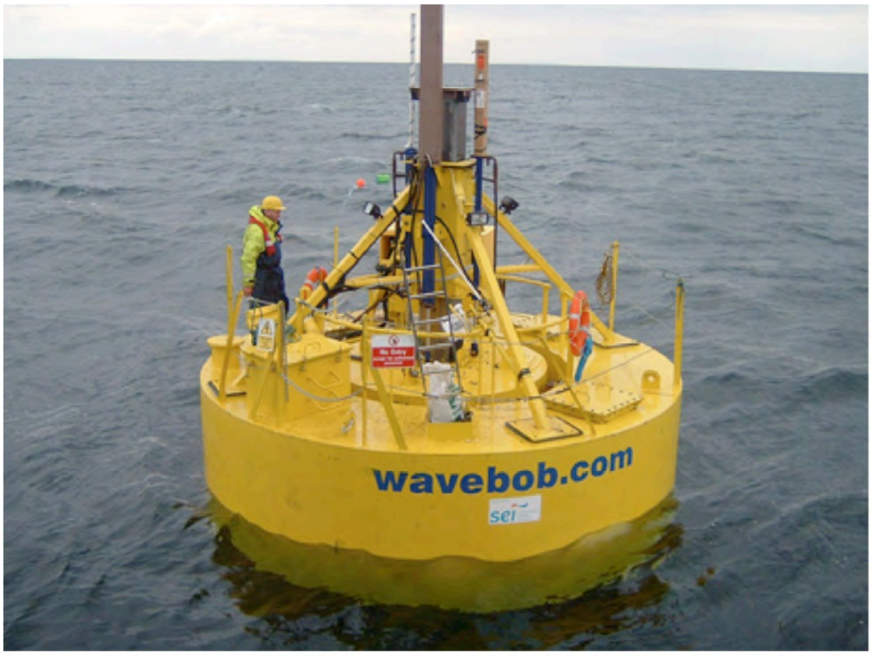


Figure 2.8: 1/4-scale WaveBob Prototype in Galway Bay, Ireland

2.3 TIDAL ENERGY DEVICES

2.3.1 Classification

A large number of tidal energy design concepts is currently under development. Putting aside barrages and impoundments, one compilation of devices (including tidal fences) indicated that over 70 tidal/ocean current devices were under development (Hales, *pers. comm.*). The European Marine Energy Centre lists 52 tidal current device developments (EMEC, 2008). Both numbers are probably a significant under-estimate, as neither includes device developments in New Zealand (of which there are at least eight) and possibly many other countries.

Despite the number of designs that have been proposed for tidal and current energy converters, there is no commonly agreed standard classification. The classification listed below breaks devices down on two criteria:

1. The source of the tidal energy to be harnessed,
2. The physical construction or energy extraction methodology (Table 2.3).

Conversion Technology	Manufacturer	Examples
Tidal Rise and Fall		
Barrages	Various	Rance River
Impoundments	Tidal Electric	None
Fences	Blue Energy	None
Tidal/Ocean Current Devices		
Horizontal Axis Turbines	MCT	SeaGen, SeaFlow
	SMD Hydrovision	TidEL
	OpenHydro	EMEC deployment
Shrouded HA Turbines	Lunar Energy	RTT 1000
Pressure Devices	HydroVenturi	Prototype trial, UK
Vertical Axis Turbines	Various	Various prototypes
Oscillating Hydrofoils	Engineering Business	Stingray

Table 2.3: Simplified Classification of Tidal Energy Converters

2.3.2 Barrages

Barrages are effectively low-head hydroelectric devices, which harness the artificial phase difference created between the rising and falling tides on the seaward side of the barrage and water being either impounded or excluded from the landward side of the barrage. Tidal barrages comprise a series of gates, which are open during the flood tide and close at high water. As the tide falls on the seaward side of the barrage, the gates are opened and the conventional hydroelectric generators are used to generate electricity.

Presently, the largest working example is the 240 MW tidal barrage on the Rance River in Northern France (PPL, 2005), although there are also smaller operational schemes in eastern Canada (Annapolis Royal: 20 MW) northwestern Russia (Kislaya: 0.5 MW). China also has five small barrages, associated with irrigation schemes, with a cumulative total of 4 MW.

Tidal barrages continue to be developed. The world's largest scheme – 254 MW at Si-hwa in South Korea - is currently under construction and is due to be Figure 2.9). At least two other major barrage projects – at Garolim and Inchon Bay - are under consideration or development in South Korea.

Figure 2.9: Si-hwa Tidal Power Plant, Korea (Artist's impression)

The UK Government has also revived a 30-year old plan to build a barrage across the tidal estuary of the River Severn between Wales and England. A recent review by the Sustainable Development Commission has shown that this huge scheme – 8,500 MW – may be viable (SDC, 2007). The UK Department of Business, Economic and Regulatory Reform is conducting further evaluation to establish the potential of Severn Estuary barrage.

Tidal barrages have high initial capital costs but are cheap to operate as there are no fuel costs and the main structure requires relatively little maintenance. Silting behind the barrage and the potentially serious environmental change caused upstream of the barrage can be problematic for consenting.

In New Zealand a number of tidal barrage proposals have been made, particularly in the five major harbours on the west coast of the North Island (Hokianga, Kaipara, Manukau, Aotea and Raglan harbours). However, the average tidal range (2 – 3 m) is small, there are significant potential environmental challenges, not least of which is the presence in some of these harbours of the rare Hector's and very rare Maui's Dolphins. Conflicting uses, such as commercial, customary and recreational fishing, are likely to make barrages a difficult, if not unattractive, option in New Zealand. For these reasons, tidal barrages will not be considered further in this report.

2.3.3 Impoundments & Constrictions

Tidal impoundments are man-made enclosures, which entrap rising flood tides, restrict their exit at high tide to create an artificial hydraulic head, which can be used to generate electricity. TidalElectric has proposed a 432 MW tidal impoundment off the North Wales/Liverpool Bay coast (PPL, 2005). This scheme involves building an impoundment wall in shallow offshore conditions and creating three compartments, which will be drained separately to smooth the power flow (Figure 2.10).

Impoundments require relatively shallow water offshore, since the principal component is a sea wall, requiring large volumes of material to be dumped and worked into the impoundment. Such structures will be critically sensitive to water depth, as it will control the volume of material required. Since most of New Zealand's coasts are reasonably steeply shelving, there are few, if any, locations where impoundments would be practical. The relatively low tidal range is also a negative factor as the natural tidal range controls the maximum hydraulic head that can be achieved within the impoundment. For these reasons, tidal impoundments will not be considered further.

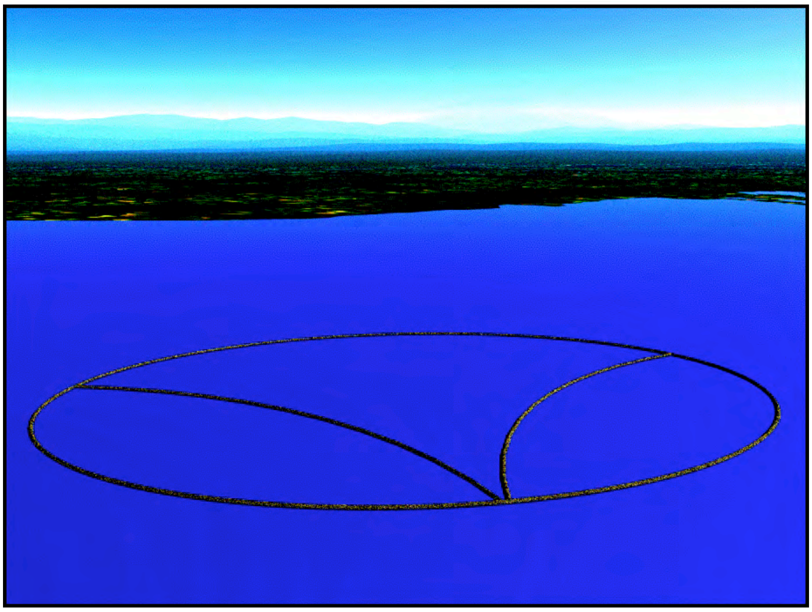


Figure 2.10: TidalElectric's 3-pool Tidal Impoundment Proposal

Tidal constrictions occur across natural harbours with narrow mouths. The large natural harbours of the west coast of the North Island (see maps in Part 5 of this report) are good examples. The natural constrictions at their mouths cause acceleration of tidal stream velocities and cause significant head differences between the harbour water level and the open sea level (effectively a phase difference between the harbour and the ocean).

Woodshed Technologies has proposed harnessing this phase difference with their Tidal Delay® technology, not by placing devices in the harbour mouth but by laying or burying water pipes across narrow isthmuses between the harbour and the open sea. The pipes will be full of water and will act as siphons. Turbines within the pipes will generate electricity from the two-way flow of water as the tides rises and falls.

Woodshed Technologies became a public unlisted company in Australia in January 2008 and has a project, through its wholly-owned UK subsidiary, CleanTechCom Limited, with another UK company to establish a trial Tidal Delay® project across the Churchill barriers between the southern Orkney Islands.

2.3.4 Tidal Fences

Tidal fences are man-made structures across narrow harbour mouths or similar sites, where tidal flows are constricted and the tidal stream velocities are accelerated. Rather than blocking or constricting the tidal flows, tidal fences contain vertical axis turbines (although horizontal axis turbines would be possible) and capture energy from the passing tidal stream. They are thus essentially passive devices, which have limited effects on the natural tidal flows. They also offer the opportunity for roads to be carried across the tidal fence.

The best example is a tidal fence is the Canadian Blue Energy range of devices. Their Ocean Turbine is based upon a Davis Hydro turbine design, which is a vertical axis turbine with vertical blades. The blades rotate in a single direction, regardless of tidal flow direction. The turbines are housed in large concrete caissons, which are moored to the seabed and can be joined to form a '*fence*' across a river or estuary mouth. Because they do not constrict flow (except coincidentally), the implications for upstream siltation are much less serious than for barrages. The Ocean Turbine has been proposed at a range of scales and six prototypes have been trialled but no commercial version has yet been built. The company is currently working to build a 20 kW demonstration device, although no date has been set for deployment.

Tidal fences are discounted for early New Zealand deployment for similar reasons to tidal barrages and impoundments – conflicting uses in harbour mouths (shipping and fishing access) and difficulties of getting consents in what will be very environmentally sensitive areas.

2.3.5 Horizontal Axis Turbines

EMEC lists over 70 active projects to develop tidal devices, which include 21 horizontal axis devices, although both numbers are probably under-estimates. Although there are significant differences in details this class of device is conceptually similar to the standard wind turbine generator, *i.e.,* a single monopole tower with an upwind rotor and turbine, connected through a gearbox to a horizontal axis generator.

There are a number of horizontal axis tidal stream turbines under development.

The best known and most advanced of which are:

1. Marine Current Turbines' SeaFlow (Figure 2.11) and SeaGen (Figure 2.12)
2. SMD Hydrovision's TidEL device
3. Clean Current Power Systems (Canada)
4. Hammerfest Strøm (Norway)

Note this grouping does not include other variants on horizontal axis turbines, including shrouded turbines (see next section) or ring turbines, like the OpenHydro device (see Section 2.3.7).

Marine Current Turbines is the clear industry leader in terms of ocean deployments. It has had a 300 kW prototype, called SeaFlow, installed off Lynmouth in Devon, UK, since 2003 (Figure 2.11). This device has been used in the tidal stream resource modelling (Section 4.3.1).

Figure 2.11: The 300 kW SeaFlow Prototype at Lynmouth, Devon

More recently, MCT has successfully installed the first utility-scale tidal stream turbine in Strangford Lough, Northern Ireland. The SeaGen device incorporates two 600 kW generators, powered by two 16 m twin-bladed turbines, mounted on a cross arm, attached to a bottom-resting monopole tower. The device was finally installed in April 2008 (Figure 2.12). The device is presently being commissioned and is due to feed electricity into the Northern Ireland grid in August-September 2008. This is thus the largest grid-connected tidal stream device yet deployed. A hypothetical version of this device has been used in the resource modelling (Section 4.3.2).

Figure 2.12: SeaGen Deployed in Strangford Lough, Northern Ireland; April 2008

2.3.6 Shrouded Turbines

There are a number of devices that use shrouds (*i.e.,* Venturi tubes) to accelerate the natural flow, because the available energy in a tidal stream flow is proportional to the cube of the velocity of the flow. The most commonly cited of these devices is the Lunar Energy device, which is based on a Scottish design (Rotech RTT). Crest Energy originally intended to deploy this device in its project (see Section 6.2.2).

Other shrouded devices include the Underwater Electric Kite and the '*TNEI*' device. The TNEI device is of interest in New Zealand because Neptune Power has proposed it as the device it will utilize for its proposed project in Cook Strait, for which it submitted an initial resource consent application in August 2007. Neptune Power's proposed project is described in more detail in Section 6.2.3.

2.3.7 Open Ring Turbines

Open ring turbine designs have been proposed but only two are presently under development. These are the Clean Current Turbines device and the OpenHydro device or "*Open-Centre Turbine*", which was deployed and is currently under test at the European Marine Energy Centre in Orkney. In both cases the device consists of an open-centred ring blade system with a separate generator on the circumference of the ring of blades. The centre of the ring is open and large enough to allow the unimpeded passage of fish and possibly small marine mammals. In the case of the

OpenHydro prototype, the device can be raised and lowered into the current. When viewed at EMEC in May 2007, the device was awaiting commissioning (Figure 2.13).

Figure 2.13: OpenHydro's Open-Centre Turbine at EMEC, May 2007 (© PPL)

In 2007 OpenHydro announced that it had won a tender to supply its Open-Centre Turbines to a project underwritten by the Nova Scotia Government, followed shortly by another announcement that it will also supply the technology to Alderney Renewable Energy in the UK Channel Islands. The Canadian development will be at a new tidal testing centre being established in the Bay of Fundy by Nova Scotia Power.

The OpenHydro device is interesting in the New Zealand context because it is the newly chosen technology of Crest Energy for its proposed project in Kaipara Harbour (Section 6.2.2).

2.3.8 Pressure Devices

There is one pressure device, called the HydroVenturi device, which is under development in the United Kingdom. The device is a submerged Venturi tube laid on the seabed or in the water column. The Venturi tube accelerates flow within it in exchange for a decrease in hydrodynamic pressure. The current small-scale prototypes have been trialled in rivers. Other pneumatic pressure devices are being developed.

2.3.9 Vertical Axis Turbines

The second largest group of devices, after horizontal axis devices, are vertical axis devices. These devices are based on the "*Darrieus*" rotor design for wind turbines, although such wind turbines are no longer under development. There are a number of such devices, including the Kobold Turbine, currently deployed in Sicily (Figure 2.14), Edinburgh Designs' variable-pitch blade design and the Blue Energy tidal fence (see Section 2.3.4).

Figure 2.14: Enermar's Kobold Turbine, Straits of Messina, Italy (© PPL)

There are at least two New Zealand-based projects, which were developing vertical axis tidal turbines. One of these projects was never made public and is currently on hold, whilst the other, Tidal Flow Seamills, is planning the deployment of a small-scale prototype device (see Section 6.2.6).

2.3.10 Oscillating Hydrofoils

There is a class of tidal stream devices, which seek to extract energy by use of oscillating or reciprocating hydroplanes. The best known of these is Stingray, which comprises a support base and a single hydroplane (although multi-plane devices were contemplated). Unlike all of the tidal devices listed above, which are passive in operation, the Stingray required active control. The device operates by active control of the angle of attack of the hydroplane, which caused it to rise or fall due to pressure from the passing current (Power Projects, 2005). The rise and fall of the hydroplane caused a pumping action in a connecting hydraulic arm, which drove a turbine and generator.

The UK designer of Stingray, the Engineering Business, successfully tested a 150 kW version of the device in Yell Sound in the Shetland Isles. However, despite attracting some Government R & D funding, the company announced in 2005 that it was discontinuing development of the device.

2.3.11 Marine Energy Devices in New Zealand

There is a wide range of options for extracting energy from waves, tides and ocean currents. Although there are some generic designs for extracting energy, most of the technologies are immature and there remains significant divergence in design. There is as yet no common design, as there is for wind turbine generators. Indeed there is unlikely to be a single design for marine energy converters, because there are so many different forms of marine energy extraction and an even greater number of mechanisms to extract that energy.

Some devices extract products other than electricity. They are not considered further here. Some extraction methodologies will most likely remain inappropriate for New Zealand conditions – OTEC, tidal barrages – and they are not considered further. Others are at an early stage – osmotic power and marine biomass – and commercial developments of other technologies may precede them.

Wave and tidal/ocean current devices have the best potential to contribute to New Zealand's medium-to-long-term electricity portfolio. It would not be appropriate or without risk to select specific manufacturers' technologies but the potential of generic technologies for deployment in New Zealand can be ranked (Table 2.4).

Energy Source	Conversion Technology	Comment
Waves		
Breaking Waves	Onshore Oscillating Water Column	Likely in new breakwater designs
	Nearshore Oscillating Water Column	Possible but difficult to consent
	Overtopping Devices	Possible but difficult to consent
	Surge Devices	Possible but limited by steeply shelving coastline
Open Ocean Swells	**Attenuators**	Possible but navigation problems for large arrays
	Point Absorbers	Probable widespread deployment of arrays
Tidal/Ocean Currents		
Tidal Rise and Fall	Barrages	Prohibitively expensive; potentially impossible to consent
	Impoundments	Very unlikely due to steep shelving coastline
	Fences	Unlikely due to competing uses; very difficult to consent
Current Devices	**Horizontal Axis Turbines** (including shrouded & open-centred turbines)	Probable widespread deployment of arrays
	Vertical Axis Turbines	Possible, subject to successful design
	Pressure Devices	Possible
	Oscillating Hydrofoils	Technology problematic

Table 2.4: Potential of Marine Energy Converter Technologies in New Zealand

NOTE: Devices in **bold red** are considered most likely to be deployed in NZ

PART 3: DEVELOPMENT OF MARINE ENERGY

3.1 INTRODUCTION

This section describes and discusses factors that control and influence the international and domestic development of marine energy. Because marine energy technologies are not yet commercially competitive with the lowest cost forms of energy – gas, wind and hydro, the role of Governments is critical in establishing targets, regulatory interventions and providing funding to encourage R & D, early-stage deployments and pre-commercial developments.

3.2 TARGETS AND FORECASTS

Most developed countries' Governments have set targets for uptake of renewable energy or, more specifically, generation of electricity from renewable sources to give their investors (including Governments' own investments) guidance on their preferred direction for energy investments. The targets may be statutory, mandatory or aspirational; short-term targets tend to be statutory or mandatory, whilst longer-term and usually much higher targets tend to be aspirational (Table 3.1).

Country	2010-15	2015-2020	2020+	Source
Australia	-	**Target: 20% of electricity**	-	Govt. target
China	-	**Target: 20% of total energy**	-	Govt. target
Denmark	-	**Target: 30% of total energy**	-	Govt. target
France	-	**Target: 20% of total energy**	-	Govt. target
Ireland	**Target: 13.2% of electricity**	**Target 33% of renewable energy by 2020**	-	Govt. target
New Zealand	-	-	**Target: 90% of electricity by 2025**	Govt. target
Portugal	**Target: 45 % of electricity by 2015**	-	-	Govt. target
Scotland	**Target: 18% of electricity by 2010**	**Aspiration: 40% electricity by 2020** *Forecast: over 50% of electricity*	*Forecast: 17 % - 30 % of all energy by 2050*	Scottish Executive
Spain **Basque Region**	**5 MW of marine renewables by 2010**			Regional energy strategy
Sweden	**Target: 6.66% of electricity**	-	-	Govt. target
United Kingdom	**Target: 10% of renewable energy by 2010**	**Target: 15% of renewable energy by 2020**		Govt. target
USA	-	-	**25% of electricity by 2025**	Industry aspiration

Table 3.1: Total Renewable Energy or Electricity Targets by Country

Key: Total energy targets, total electricity targets, aspirational targets, forecasts

Relatively few countries to date have set specific targets for marine energy but those that have tend to be the ones that have had the longest developments in or biggest commitment to investment in marine energy. A growing number of countries are making forecasts of, if not setting targets for, the likely contribution of marine energy to electricity or total energy supply, *e.g.,* the Basque region in Spain.

3.2.1 Renewable Energy and Electricity Policy Targets

Most developed countries have now established renewable energy or renewable electricity targets as part of wider packages to reduce GHG emissions and increase uptake of renewables. The European Union has set a binding target on its 27 members of 20% of energy consumption to come from renewable sources by 2020 and has agreed individual targets with each of its member nations, ranging from 10% to 49% (REN21, 2008). The following focusses on nations active in developing marine energy.

The UK has set a target of 10% renewable energy by 2010 and had originally set an '*aspirational*' goal of 20% renewable electricity generation by 2020. However, this was scaled back in October 2007 to 15%. The Scottish Executive has set a more aggressive target than the British Government for Scotland – an 18% target by 2010 (apparently already achieved), to be followed by a target of 40% of electricity generation from renewable sources (most likely, new wind, hydro but including marine) by 2020. In 2007 Ireland set itself a target of 15% of renewable energy use by 2010 and 33% by 2020 with a strategic goal to accelerate uptake of renewable energy.

The Chinese Government's declared target is to supply 10 per cent of energy (60 GW) from renewables by 2010 and 120 GW by 2020. About 50 GW of the 2010 target is expected to come from small hydro and 10 GW from wind and biomass. China is at the same early stage as New Zealand in developing its marine energy potential.

As part of the New Zealand Energy Strategy the Government has set a target of 90% renewable electricity generation by 2025, although it has not set any technology-specific targets.

3.2.2 Specific Marine Energy Uptake Targets

Despite the large number of countries with renewable energy targets, few have set specific marine energy targets (Table 3.2).

Perhaps most aggressively Portugal has an '*indicative*' target of 50 MW of installed wave power by 2010 but this may have been an aspiration, rather than a formal target (EREC, 2004). Either way, the delays to installation of the Pelamis devices at Aguçadoura and other device installations are likely to mean that this target will not be met. The 550 MW target by 2020 may not be easily achieved in light of these recent delays.

The Spanish renewable energy association (APPA) has indicated that there are 13,000 MW of potential marine energy around Spain's coasts and has proposed a 50 MW target for new marine energy projects (APPA, 2007). There are currently five wave projects in development: 3 x OWC projects, one OPT PowerBuoy project (Santoña) and one Pelamis project (Muxia). Two of these projects are within the Basque region, which has a regional energy strategy target of 5 MW of wave power installed by 2010.

Despite the advanced state of regulatory thinking and commitment to marine energy by the United Kingdom, it has not set any firm targets for uptake of marine energy.

Country	2020	2050	Source
Ireland	Forecast: 84 MW installed Target: 500 MW installed	Forecast: 485 MW Installed	Ocean Energy in Ireland – SEI – 2005
New Zealand	1 - 2% of electricity	-	Energy Outlook to 2030
Portugal	Target: 550 MW installed	-	Government Target
Scotland	Forecast: 10% of Scotland's electricity production	-	Marine Energy Group Report (2004)
Spain **Basque Region**	5 MW off Basque coast by 2010	-	Basque Region Energy Strategy
United Kingdom	Forecast: 3% of UK's electricity	Target: 20% of UK's electricity	Carbon Trust Report (2006)

Table 3.2: Marine Energy Targets and Forecasts by Country

Key: Total energy targets, total electricity targets, aspirational targets, forecasts

The UK Government has forecasted that marine energy could supply up to 3% of electricity supply by 2020 (as part of its overall target of 15% of energy supply from renewable energy resources). It also has an aspirational target for marine energy to supply 20% of electricity by 2050. As part of its proposed targets, Ireland has proposed a target of 500 MW of installed ocean energy capacity by 2020 with an interim target of 75 MW by 2012, underpinned by investment to accelerate technology developments and solutions to infrastructural and economic issues.

3.2.3 Developers' Commercialization Strategies

Developers' appetite for investment may depend on individual countries' resources and general environment but their individual commercialization strategies are also important. Marine energy device developers adopt a range of different commercialization strategies, of which the end-members are:

1. Pure device developers (*e.g.,* Pelamis Wave Power, Marine Current Turbines)
2. Pure project developers (*e.g.,* international energy companies, such as Chevron and Total, and major European utilities, such as Scottish Power and EdF), which invest in projects, utilizing more than one technology

Between these end-members are device developers, who also invest in their own deployment projects (*e.g.,* Ocean Power Technologies, Finavera). As marine energy technologies mature, the industry is likely to see increasing participation by investors, such as international energy companies and utilities, which have little direct involvement in specific technologies. These organizations will probably accelerate the pace and spread of project developments.

3.3 FUNDING MECHANISMS

Most developed countries also have supportive policies in place to promote the uptake of renewable energy to meet the targets set out in the previous section. There are a number of different mechanisms, which promote renewable energy or, more particularly, individual forms of renewable energy.

The three most common mechanisms are:

1. Government-funded capital grant programmes
2. Renewables obligations
3. Feed-in tariffs

The following sections focus on the best-known schemes and those that specifically promote uptake of marine energy technologies. Other support mechanisms, such as production tax credits, net metering and direct investment loans have not been applied to marine energy technologies. Some Governments have a portfolio of funding mechanisms from R & D funding to feed-in tariffs to stimulate both '*technology push*' and '*market pull*'.

3.3.1 Capital Grant Programmes

The British Government introduced capital grant schemes to provide incentives for marine energy deployments in their waters. The UK's Marine Renewables Deployment Fund (MRDF) was established in February 2006 and offered £ 42 million (NZ$ 111 million) for deployments in UK waters. Developers complained that the funding process was arduous and the criteria for funding were too severe, particularly the requirement that devices had to demonstrate 3 months' continuous deployment to qualify for funding. This qualification was relaxed to 3 months' cumulative deployment. However, at the time of writing only two projects had applied for funding from the MRDF and none had been awarded funds (RAB, 2008).

The Scottish Executive had a similar scheme of capital grant awards totalling £ 13 Million (NZ$ 34 million), called the Wave and Tidal Energy Support scheme (WATES). The WATES scheme opened between October 2006 and in February 2007 gave varying amounts to 9 projects to establish deployments – largely at the European Marine Energy Centre – in 2008.

In New Zealand the Minister of Energy introduced the New Zealand Marine Energy Deployment Fund (MEDF) on 17 October 2007. The MEDF is designed to encourage device developers to deploy devices in New Zealand waters. The fund is $ 8 million, nominally $2 million per year for 4 years. The criteria for awards are somewhat less onerous than the UK's MRDF scheme. Two bids were received by the closing date of the first round on 29 February 2008 (NZ Government 2007d). The Minister announced the first award ($ 1.85 million), to Crest Energy on 29 May 2008 (subject to grant of a resource consent for the project). He also confirmed that the second round would open on 31 July 2008 and close on 24 November 2008. The next awards are likely to be announced in May 2009.

The Fund will award up to $2 million *per annum* for three further years to co-fund prototype deployments in New Zealand waters. The awards are relatively small in terms of the costs of deployments but they are clearly attractive to developers, who must at least match the financial contribution from the MEDF. The Fund is clearly stimulating both interest in New Zealand from overseas and deployment activities.

3.3.2 Renewables Obligations

Also called renewable portfolio standards (RPSs), renewables obligations are requirements on electricity generators to supply electricity from specified renewable energy resources. ROs are essentially used by Governments to promote the development and uptake of specific technologies, *e.g.,* wind and marine, which cannot compete initially with established forms of fossil fuel generation. Generating companies acquire Renewable Obligation Certificates (ROCs) for electricity produced from eligible wave or tidal energy generators or, alternatively, pay a higher buy-out fee. In the UK the Government pays £ 0.34/MWh of electricity produced and the generator acquires one (ROC) for each MWh generated. From April 2009, marine-generated electricity will get two ROCs at prices set according to generation market electricity prices.

Scotland has advanced further with a specific scheme for the uptake of marine energy, called the Marine Supply Obligation (MSO), which was introduced in April 2007. Qualifying generation capacity must demonstrate a minimum period of operation, a capacity factor and an availability factor. The MSO will pay £17.5p/kWh (NZ$ 46c/kWh) for wave-generated electricity and £10.5p/kWh (NZ$ 28c/kWh) for tidal stream-generated electricity. There is a capacity limit of 75 MW of generation that will be supported under this scheme. Projects are already being commissioned to take advantage of this scheme, *e.g.,* Wavegen's new proposal in Siadar Bay on the Isle of Lewis in Scotland.

3.3.3 Feed-in Tariffs

Since feed-in tariffs were introduced in the US in 1978, they have been effective in increasing interest, investment and innovation in new technologies. They have been particularly effective in promoting wind and solar projects but they are being applied to marine projects too. A similar feed-in tariff in Germany for solar PV installations and wind generation has made it the biggest user of both within 10 years.

With respect to marine energy feed-in tariffs, the best known are the schemes for marine energy in Portugal, Spain, Ireland and Scotland. Portugal has by far the most generous feed-in tariff for marine energy deployments: € 23c/kWh for the first 12 MW of wave energy generation installed for 10 years. As a result there are now at least four projects under development, all of which involve overseas device developers, deploying in Portuguese waters.

In Spain until 2004 marine energy projects could receive the same feed-in tariff as onshore wind installations but, in that year, the Spanish Government introduced a specific feed-in tariff for wave and tidal energy (and geothermal energy) of € 6.89c/kWh for the first 20 years, followed by a € 6.51c/kWh for subsequent years. For the first 15 years a specific tariff can be fixed for each installation. There are now at least three major projects, involving overseas device developers, now being built in Spain.

Ireland has a Renewable Energy Feed in Tariff (ReFIT) in 2006 with different values of support for different renewable technologies. It offers a € 22c/kWh tariff for marine energy-generated electricity.

3.4 REGULATORY MECHANISMS

In addition to funding mechanisms, Governments have taken a number of other steps to promote marine energy through regulatory interventions. These include establishment of marine energy centres, reduced permitting requirements for demonstration zones and space/resource allocation regimes. In reality there is something of a continuum between these regulatory initiatives.

3.4.1 Marine Energy Testing Centres

The United Kingdom established the first marine energy testing centre, the European Marine Energy Centre (EMEC), in the Orkney Isles in 2004. It now has a hierarchy of testing centres, ranging from the New and Renewable Energy Centre (NaREC) - for testing scale prototypes, to EMEC - for full-scale prototype testing in open-sea conditions and WaveHub - a new facility of the Cornish coast for supported commercial projects involving multiple devices. Other countries have followed the UK's lead: wave and/or tidal testing centres are now under development on the

Pacific and Atlantic coasts of Canada and the United States. Smaller-scale testing centres, in more sheltered locations, have been in established at Nissum Bredning in Denmark (see Figure 2.4) and Galway Bay, in the lee of the Aran Islands, off the west coast of Ireland (see Figure 2.8).

3.4.2 Permitting for Prototype/Demonstration Projects

The United Kingdom has established a protocol for permitting of demonstration projects, which is used at EMEC and elsewhere (DTI, 2005). Marine energy testing centres have reduced permitting requirements, insofar as '*blanket*' consents may have been granted to a centre for deployment with developers having to supply information to consenting authorities on effects specific to their devices, rather than full consents. They may have coincidentally reduced the competition for deployment sites at other locations.

3.4.3 Space/Resource Allocation Regimes

In the United States, the Federal Energy Regulatory Commission (FERC) introduced a reduced permitting scheme in 2007 for temporary demonstration projects. This scheme is a hybrid between a demonstration project permitting regime and a space/resource allocation regime. Developers can apply for a FERC consent, which would be a '*fast-track*' process relative to conventional permitting, although the developers still have to secure State permits before projects can proceed.

At present the FERC scheme appears to be the only dedicated marine energy space/allocation regime. Such a regime may be appropriate for marine energy projects in New Zealand to avoid the unregulated '*land grab*' that occurred with respect to aquaculture in the early 2000s and led to the current moratorium on aquaculture developments. A planned approach to marine energy developments, in much the same way as the oil and gas exploration permitting regime works, would ensure orderly and viable developments take place.

3.5 INDUSTRY DEVELOPMENTS

Industry developments depend on the maturity of the current industry and the ability and willingness of existing suppliers to other industries coming together to form a supply chain for a new marine energy industry. A key feature of development of such an industry in the UK has been the formation of strategic partnerships between developers and their suppliers and investors. Lastly, the pace of industry development will be controlled by the confidence of private investors to participate in the industry, taking a lead from Government investment.

3.5.1 Supply Chain Maturity

There is currently no marine energy supply chain in New Zealand, since no projects of any significant scale have yet been proposed. However, the necessary components of a supply chain are in place – working in other industries – and will be brought to bear on marine energy quickly, if economic and profitable opportunities exist. However, New Zealand does not have the benefit of over-supplied industries, such as the offshore oil and gas industry in the UK, looking for future opportunities in related fields.

New Zealand has the key components of a marine energy supply chain, running from entrepreneurial project developers to buyers of marine-generated electricity. However, that supply chain may have little depth, *i.e.,* very limited number of suppliers in one '*link of the chain'*. It may also have some gaps, particularly in terms of engineering facilities and equipment. Such a gap – in steel-rolling capacity – was identified when wind project developers sought to fabricate wind turbine towers in New Zealand.

AWATEA has recently completed a consortium-funded study, undertaken by Power Projects Limited, looking at the current status of the marine energy supply chain in New Zealand. The study has two outputs – a supply chain ‘gap’ analysis and a Supply Chain Directory of current companies, consultants and organizations, which are or could contribute to a strong domestic supply chain. The Supply Chain Directory was published and distributed on 29 May 2008. The Gap Analysis report will be completed in July 2008.

3.5.2 Strategic Partnerships

One of the hallmarks of mature marine energy projects in the United Kingdom is that the lead developer engages with a wide range of potential investors, suppliers and supporters-in-kind. At one stage in 2006 the Ocean Power Delivery (now Pelamis Wave Power) website listed 29 consortium partners in the project, making contributions from R & D to equipment supply.

By contrast most current domestic marine energy projects have a single entrepreneur or partnership without the depth of investors, suppliers and supporters-in-kind, which will be necessary to make their first deployments possible. The WET-NZ R & D programme is unusual in having three contributing parties in the consortium.

3.5.3 Investor Confidence

As noted in the previous section, successful projects require a range of participants, beyond the initial entrepreneur/investor. Although New Zealand has yet to see the range of participants involved in domestic projects, they will clearly be necessary to make deliver successful results.

It is encouraging to see international oil and gas companies (energy companies), investing in marine energy projects. For example, Total is a joint venture partner with Ocean Power Technologies in project developments in Spanish and French waters, whilst Chevron’s technology venture company has invested recently - in Wavebob. Several major European generation, transmission and distribution utilities, such as Vattenfall, Statkraft, E.On and RWE, have invested in projects, particularly in Scotland. The venture capital community has been a small contributor, particularly to the Pelamis project. To date interest amongst energy companies and utilities in New Zealand’s marine energy projects (see next section) has not extended to any public investment in projects.

3.6 SUMMARY

Ultimately the widespread deployment of marine energy technologies will depend on developers being successful in reducing capital costs and operating costs, so that the unit cost of electricity from a marine energy converter is competitive with lower cost forms of energy, such as gas-fired Combined-Cycle Gas Turbines, geothermal and wind power. Otherwise, marine energy will have but niche application.

Whilst international energy developments, such as the persistent high price of oil, international efforts to set a price for carbon and the establishment of national and international emissions trading mechanisms, will promote renewables, the unit cost of marine energy will fall only through continuing deployments and economies of scale in commercial production.

Governments, including that of New Zealand, have done much to provide incentives for marine energy, including capital grant programmes (such as the MEDF in New Zealand), renewables obligations, feed-in tariffs and introduction of regulatory assistance. Continuing developer commitment and growing investor confidence will provide the remainder of the momentum to encourage the development of marine energy both in New Zealand and overseas.

PART 4: WAVE & TIDAL ENERGY RESOURCE ASSESSMENT

4.1 INTRODUCTION

Whilst a number of public and unpublished projects have identified potential areas for marine energy projects in New Zealand, there has been no attempt to quantify the resources available for commercial extraction.

4.1.1 Marine Energy Resources and Extractable Reserves

There is some confusion in publications as to whether figures cited for particular areas represent the natural wave or tidal/ocean power available (albeit expressed as MW of potential electricity generation) or whether they represent the harnessable energy that can be commercially extracted. Whilst it is relatively easy to make rough assessments of the naturally available power, it is much more difficult to make assessments of the extractable energy.

For example, it has been proposed that the tidal flows into and out of Kaipara Harbour are equivalent to 11,000 MW of potential electricity. However, Crest Energy's proposal to install only 200 MW of tidal stream generators in the main body of the channel leading to the harbour mouth clearly demonstrates that the extractable energy is a small fraction of the potential energy. Similarly, there has been a estimate that the tidal/ocean currents in Cook Strait could contain 13,000 MW of potential electricity generation. Mapping undertaken in this project shows that the areas where currents reach sufficient speeds to be attractive for generation are a much smaller part of the Strait and, even there, water depth and competing uses may be a constraint on areally extensive generation schemes.

4.1.2 Potential Marine Energy Projects

Previous reports on marine energy in New Zealand have taken different approaches to determining the potential for marine energy projects. PB Power reviewed the status of marine energy technology developments and tried to derive both unit device and array sizes (PB Power, 2006). They also reviewed the available marine energy resources but made no attempt to combine technologies and resources to assess potential target areas or project sizes.

Sinclair Knight Merz (SKM) undertook a number of Regional Renewable Energy Assessments, available on the EECA website (SKM, 2006-08), which used simple '*rules of thumb*' to derive potential marine energy reserve sizes within each studied region. SKM took the approach of assessing the regional potential wave and tidal energy resources and then trying to assess the potential of a small range of marine energy technologies within each region. By and large their studies did not identify specific projects or sites, where projects might be conducted.

Venture Southland undertook a review of the energy potential of the Southland region, including wave and tidal energy, but no estimates of the potential resources or reserves were calculated (Venture Southland, 2003). Power Projects Limited estimates that the potential wave energy reserves off the coast of Southland could exceed 2,000 MW with more than 100 MW of tidal/ocean current potential. Together these studies indicated a combined potential for marine energy around the coast of New Zealand in excess of 8,000 MW, just short of the current national electricity generation capacity (Table 4.1).

These numbers should be treated with great caution. They are not based on a detailed economic evaluation, since the cost of mature wave and tidal energy generation technologies has yet to be established. The best conclusion that can be drawn is that wave and tidal energy reserves are likely to exceed the country's requirements for electricity derived from these sources. The country will continue to have a wide ranging portfolio of generation assets, which will include marine energy, if the price of marine energy generation technologies can be brought down sufficiently to be competitive with other forms of generation (*e.g.,* wind, hydro and geothermal).

Source	Location	Wave (MW)	Tidal (MW)
Regional Renewable Energy Assessments SKM (2006 – 08)	North Island (ex. Wellington CMA)	~2,500	>40
	South Island (ex. Southland)	~2,500	>30
This report Power Projects Ltd	Wellington CMA	?	>300
	Southland	~2,000	>100
TOTAL		**>7,000**	**>500**

Table 4.1: Summary Estimates of Wave and Tidal/Ocean Current Reserves

Note: the numbers above should be cited with **great caution,** taking account of the summary nature of the calculations.

A three-stage approach has been used in the analysis reported here:

1. New modelling of wave and tidal/ocean currents around New Zealand, including site-specific analysis of six potential wave sites and two potential tidal/ocean current sites. The new modelling is based upon hindcast data, validated against a number of wave buoy and measured tidal/ocean current data.
2. Development of power spectra for three notional wave devices and two notional tidal/ocean current devices. Devices chosen were modelled on the existing or generic devices.
3. Application of the power spectra to the wave and tidal resource at the specific sites to derive electrical production data.

The aim of the analysis reported here was not to identify specific sites at which projects could be undertaken with specific technologies: that will be work undertaken – in much more detail – by project developers as part of a full commercial proposal for their projects, ahead of submitting consent applications to the appropriate regional and local authorities. The present study therefore seeks to link high-graded areas with potential technologies without going to the next level of detail – to determine an economic value for a project proposed in each area.

4.2 WAVE DEVICE MODELLING

It is essential to understand the performance characteristics of any wave energy converter (WEC), in order to characterize the power produced by the device. More technical detail on wave device modelling can be found in Appendices B & C at the end of this report. The following is a layperson's summary.

There are a variety of different wave energy conversion methods and different device designs under development, as described in Sections 2.2 and 2.3. These come in a range of sizes and generation capacities. Performance characteristics are generally more difficult to characterize than for other forms of renewable energy, because the power produced by a wave energy converter is generally dependent on multiple parameters.

Raw wave power - the energy flux within a wave field - is proportional to the wave period (T) and the square of the wave height (H_{sig}^2). The significant wave height (H_{sig}), which is the statistical average of the highest 1/3rd of the incident waves, is used in place of average wave height.

Raw wave power (in kW/m of wave-front) can be found approximately from the following formula:

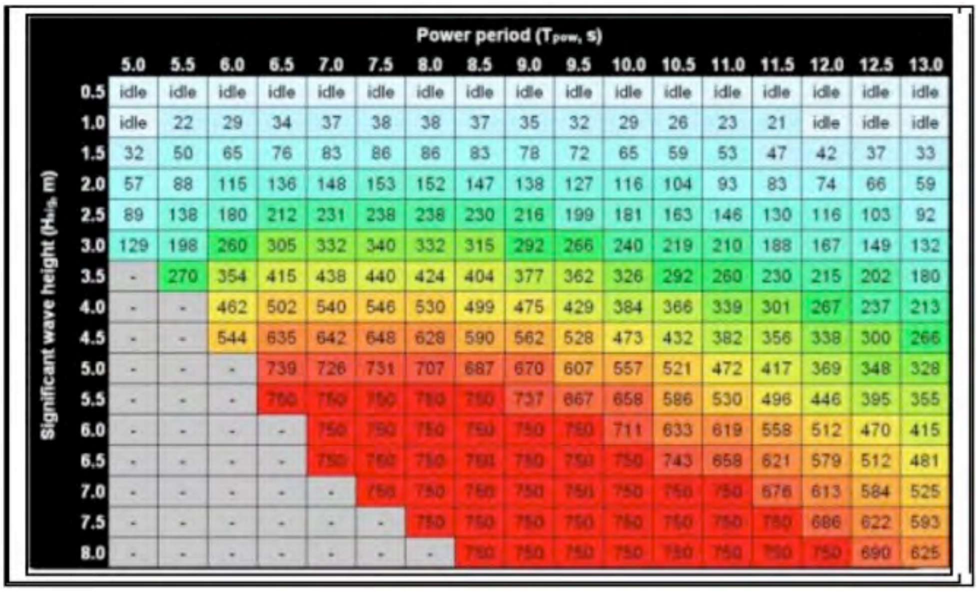
$$P = \frac{\rho g^2}{32\pi} H_{sig}^2 T \approx (1.0 \frac{kW}{m^3 \cdot s}) H_{sig}^2 T$$

Similarly, the power captured by the action and operation of a device is also dependent on both the wave height and the period. In an ideal world technology developers would publish accurate performance characteristics that had been thoroughly calibrated through testing and operational experience. In the real world most WEC developments are not sufficiently advanced to derive these performance characteristics. In any event, most WEC developers are either unable or unwilling to release this information.

4.2.1 Pelamis P750

One developer that has previously published data for their WEC is Pelamis Wave Power, which published a '*power matrix*' for the Pelamis P750 device in 2004 in one of their marketing documents (Figure 4.1). Unfortunately, the matrix is probably now slightly out-of-date and has not been updated. Although this published '*power matrix'* serves as a useful template for the industry, it remains one of the only data sets on any WEC currently in the public domain. The '*Power Matrix*' approach can also be misleading in that it provides little information about the response of the device to spectral shapes, spreads or directions of wave propagation.

The Pelamis power matrix has been used in this study to assess the wave energy potential of selected sites around the coast of New Zealand. These sites are thus identified as particularly appropriate, although not exclusively so, for use with the Pelamis P750 device and its successive modifications.

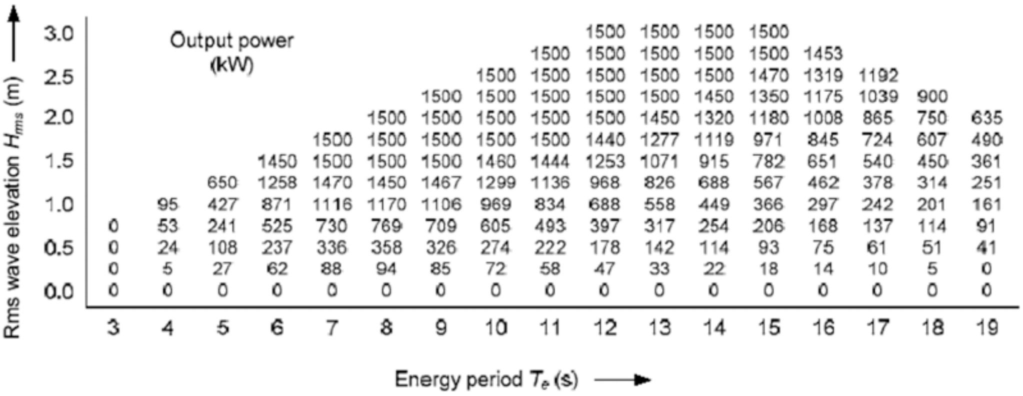


Significant wave height (H_{sig}, m)	Power period (T_{pow}, s)																
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Figure 4.1: Pelamis P750 Power Matrix (OPD, 2004)

4.2.2 Scaled 1.5 MW Pelamis or Attenuator

A scaled ‘commercial’ version of the Pelamis power matrix was produced by University of Edinburgh to anticipate changes in the overall structure and performance as it developed towards full commercial realisation (Figure 4.2; Scottish Executive, 2006). This matrix was also applied in the analysis of the chosen sites around the coast of New Zealand.



Output power (kW)

Rms wave elevation H_{rms} (m)

Energy period T_e (s)

	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
3.0										1500	1500	1500	1500				
									1500	1500	1500	1500	1500	1453			
2.5								1500	1500	1500	1500	1500	1470	1319	1192		
							1500	1500	1500	1500	1500	1450	1350	1175	1039	900	
2.0						1500	1500	1500	1500	1500	1450	1320	1180	1008	865	750	635
					1500	1500	1500	1500	1500	1440	1277	1119	971	845	724	607	490
1.5				1450	1500	1500	1500	1460	1444	1253	1071	915	782	651	540	450	361
			650	1258	1470	1450	1467	1299	1136	968	826	688	567	462	378	314	251
1.0		95	427	871	1116	1170	1106	969	834	688	558	449	366	297	242	201	161
	0	53	241	525	730	769	709	605	493	397	317	254	206	168	137	114	91
0.5	0	24	108	237	336	358	326	274	222	178	142	114	93	75	61	51	41
	0	5	27	62	88	94	85	72	58	47	33	22	18	14	10	5	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.2: Scaled 1.5 MW Pelamis Power Spectrum

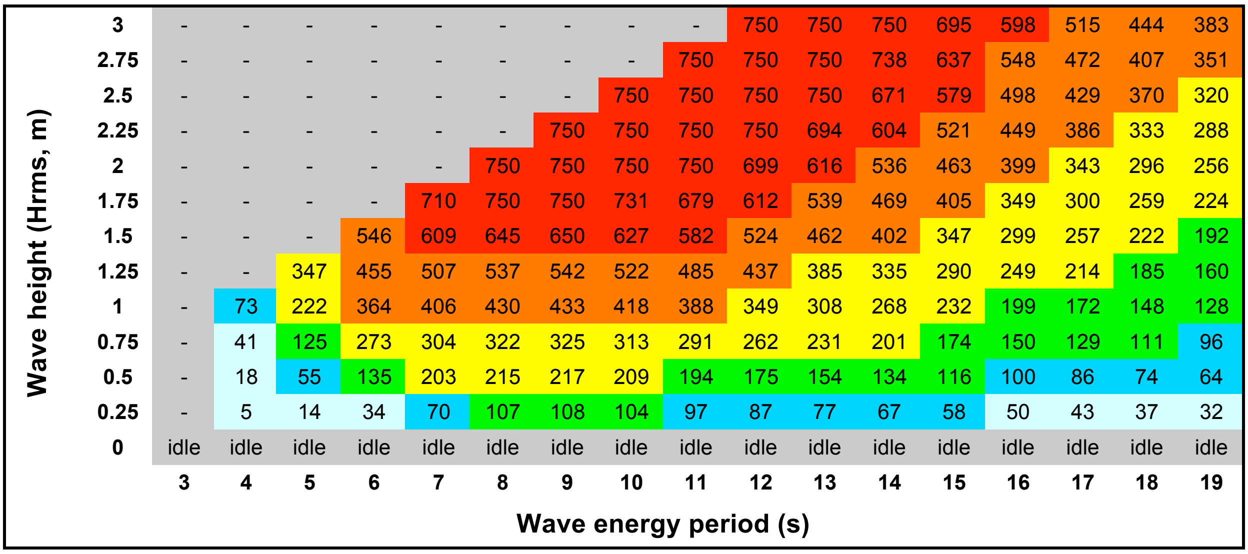
These figures are superficially similar but note that the axes are different:

1. The ranges and scale intervals of the X axes are different
2. Y axis values (ordinate) are inverted in Figure 4.2. More importantly, the statistical measure H_{rms} is used in place of H_{sig}, although H_{sig} is widely regarded as the industry standard. Note: $H_{rms} = H_{sig}$ divided by √2.

4.2.3 Generic 750 kW Point Absorber Device

An extensive literature search did not identify any other published power matrices for offshore WEC devices. To fulfill the scope of the study, and to better represent the spread of technologies under development, a generic Point Absorber device was modelled resulting in the matrix shown in Figure 4.3.

The methodology behind this approach is somewhat simplistic but functional. It involves a basic interpretation of wave power theory, as developed by Falnes (2002b & c) and others, and was not intended to be comprehensive or device specific. Further details are beyond the scope of this report but are available in Appendix C.



Wave height (Hrms, m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
3	-	-	-	-	-	-	-	-	-	750	750	750	695	598	515	444	383
2.75	-	-	-	-	-	-	-	-	750	750	750	738	637	548	472	407	351
2.5	-	-	-	-	-	-	-	750	750	750	750	671	579	498	429	370	320
2.25	-	-	-	-	-	-	750	750	750	750	694	604	521	449	386	333	288
2	-	-	-	-	-	750	750	750	750	699	616	536	463	399	343	296	256
1.75	-	-	-	-	710	750	750	731	679	612	539	469	405	349	300	259	224
1.5	-	-	-	546	609	645	650	627	582	524	462	402	347	299	257	222	192
1.25	-	-	347	455	507	537	542	522	485	437	385	335	290	249	214	185	160
1	-	73	222	364	406	430	433	418	388	349	308	268	232	199	172	148	128
0.75	-	41	125	273	304	322	325	313	291	262	231	201	174	150	129	111	96
0.5	-	18	55	135	203	215	217	209	194	175	154	134	116	100	86	74	64
0.25	-	5	14	34	70	107	108	104	97	87	77	67	58	50	43	37	32
0	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle

Wave energy period (s)

Figure 4.3: Generic 750 kW Single Point Absorber

4.3 TIDAL & OCEAN CURRENT DEVICE MODELLING

Modelling of tidal/ocean current devices is different from modelling for wave devices as the time component of the resource is of a different scale. Tidal stream devices operate, using the same principle as wind turbine generators – generating power directly from the water current. The recoverable tidal stream power is limited by:

1. Characteristics of the site (water depth, vertical flow profile, turbulence)
2. Environmental conditions (impact of the device on the tidal stream)

More detail on the modelling of tidal/ocean current devices can be found in Appendix C at the end of the report. A layperson's summary follows here.

The focus in tidal/ocean current device modelling is on assessing the instantaneous power that can be extracted from the currents incident on the device and then assessing the recoverable power derived from the device, acknowledging the various losses in transferring the kinetic energy in the current to electrical power produced by the generator.

The losses include:

1. Coupling of the device's active surfaces, *e.g.,* blades, with the current flow, swept area of the blades
2. Mechanical inefficiencies in the turbine, drive train, generator and power conditioning equipment.

These losses are additive: small losses in one component (say 5%) mount up, so that total efficiencies may be as low as 40%, *i.e.,* only 40% of the power available in the tidal stream is converted to electrical power. There are also likely to be periods when current flows are too low to turn the blades (*i.e.,* below the '*cut-in speed*' of the device) and periods when the tidal flow exceeds the rated power of the device, so the device produces at its capacity, rather than that of the available current.

Tidal current velocity is critical in site selection because the power available varies as the cubic function of the current velocity. Put simply, a doubling of the current velocity causes an eight-fold increase in the available power.

Two generic tidal stream generators have been modelled in this study. The performance derives from power spectra, which are based on, but are not identical to, the following:

4.3.1 SeaFlow 300 kW Tidal Stream Generator

The Marine Current Turbines' SeaFlow generator has been deployed off Lynmouth in Devon since 2003 (see Section 2.3.5). It has a twin-bladed (11 m diameter) horizontal axis upstream rotor, driving a turbine generator, mounted on a monopole tower, which has been drilled into the seabed (Figure 2.11). The generator can be raised from and lowered into the tidal current flow and is capable generating 300 kW.

4.3.2 SeaGen 1.2 MW Tidal Stream Generator

Marine Current Turbines' SeaGen Generator is the pre-commercial successor to SeaFlow (see Section 2.3.5). It was deployed in Strangford Lough, Northern Ireland, in April 2008 and is currently being commissioned. It differs significantly from its predecessor, principally in having two turbines mounted at each end of hydrofoil, which can be raised and lowered on the monopole tower. The twin-bladed rotors (16 m diameter) drive two retractable 600 kW-rated turbines (Figure 4.4).

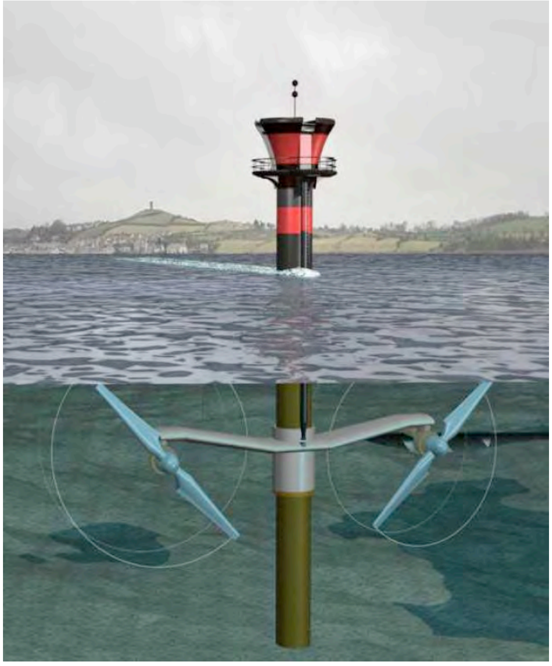


Figure 4.4: Artist's Impression of SeaFlow Device

NOTE: there was no intention in the modelling that these specific devices were being actively considered for deployment – they were merely used to derive generation performance estimates.

PART 5: POTENTIAL MARINE ENERGY PROJECTS IN NEW ZEALAND

Part 4 reviewed the definitions of wave and tidal/ocean current energy resources and described the methodology for determining potentially extractable resources by modelling three wave and two tidal stream devices. The next step is to integrate the performance characteristics of the chosen devices with resource assessments at selected locations to calculate their generation potential.

5.1 WAVE ENERGY POTENTIAL LOCATIONS

Mapping the wave and tidal/ocean current resources around the New Zealand coast is a major undertaking. Characterizing the wave environments and potential resources is complex and time-consuming. The MetOcean Solutions Limited report (Appendix C) contains a detailed technical explanation of the mapping and assessment of national, area and site-specific wave resources and presents a wider range of maps and tables than is contained here. What follows is a summary of the modelling and mapping with a simplified interpretation in layperson's terms.

There is a generally accepted '*rule of thumb*' for wave energy projects, which will assist an understanding and evaluation of the maps of the wave resources that follow. A mean spectral wave power of greater than 20 kW/m in an area indicates potential for wave energy projects there. The actual requirements of a particular site are clearly much more detailed.

The maps presented here are based on a 10-year hindcast (1998-2007) and comprise two maps that characterize the resource:

1. Mean significant wave height – this parameter is approximately the mean (Figure 5.1)
2. Mean spectral wave power – the flux of potential energy associated with the wave spectrum (Figure 5.2)

There are also three further maps, which integrate the power spectra from the three wave devices to derive the potentially extracted power from each device. These maps are:

3. Mean power output from the modelled 750 kW Pelamis device (Figure 5.3)
4. Mean power output from the modelled 1,500 kW variant of a Pelamis device (Figure 5.4)
5. Mean power output from the modelled 750 kW single point absorber (Figure 5.5).

These maps are representation of the power that could be extracted by a single unit of each of three modelled wave devices at any point on the map. it is very unlikely that single devices will be deployed for commercial applications, other than as early stage prototypes.

5.1.1 National & Regional Distribution of Potential Locations

The following maps demonstrate that there is a wide range of potential locations for wave device deployments. The same is not true for tidal/ocean current device deployments (see Section 5.3.1). For waves, almost any location on west- or south-facing coasts will have significant potential for wave projects. A range of west, south and east coast locations have been modelled to demonstrate the potential variability of electricity production around the New Zealand coast.

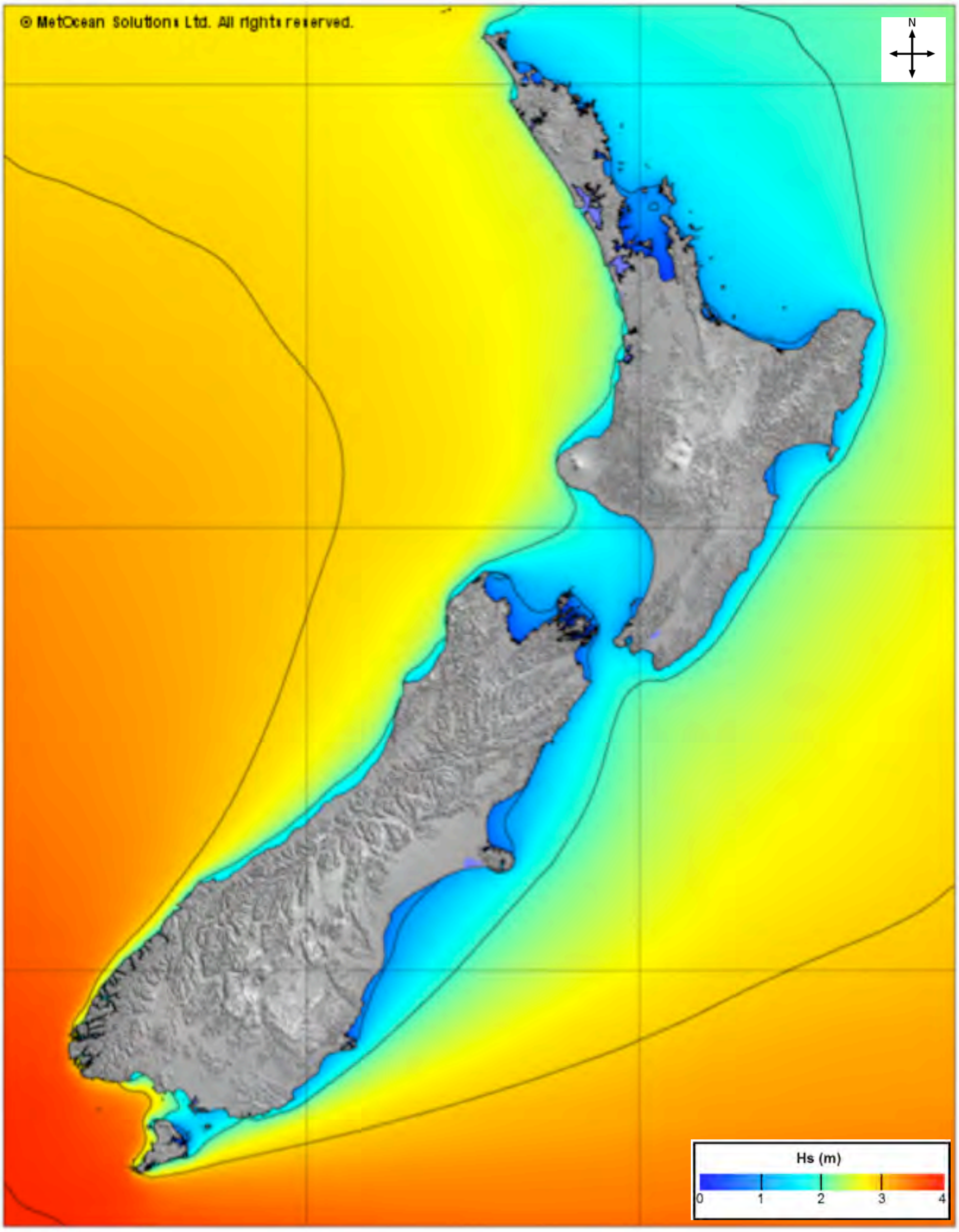


Figure 5.1: National Mean Significant Wave Height (1997-2007)

Mapping of the wave energy resources around New Zealand shows that most of the New Zealand CMA (and EEZ) has waves with a mean significant wave height of more than 2 m (Figure 5.1). There is a general gradient of declining wave height from southwest to northeast. Wave heights exceed 2 m very close to west- and south-facing coasts. Close to the coast and on north- and east-facing coasts, where the main islands provide some shelter from the prevailing south-westerly swell and wave directions, nearshore significant wave heights are less than 2 m.

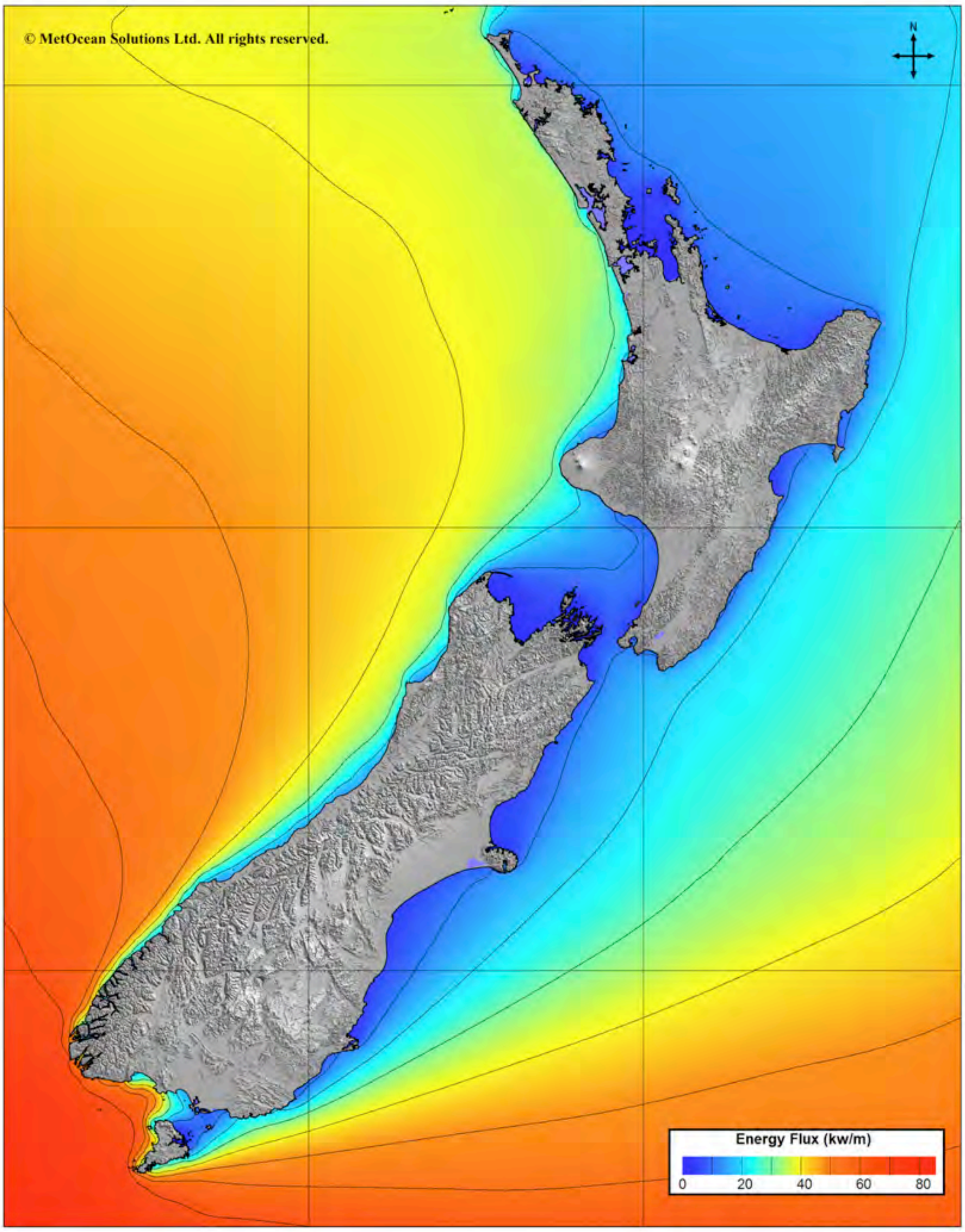


Figure 5.2: National Mean Spectral Wave Power (1997-2007)

The mean spectral wave power is a measure of the wave energy flux at any location (Figure 5.2). Mean spectral wave power is measured in units of kW per metre of wave front (kW/m). It is also common to cite the mean spectral wave power, usually measured from a wave buoy, for any measured location. Note that the figures on this map have been validated against six wave buoy locations: the hindcast data are an accurate reflection of the measured wave resource (see Appendix C, Section 3.4, for validation details).

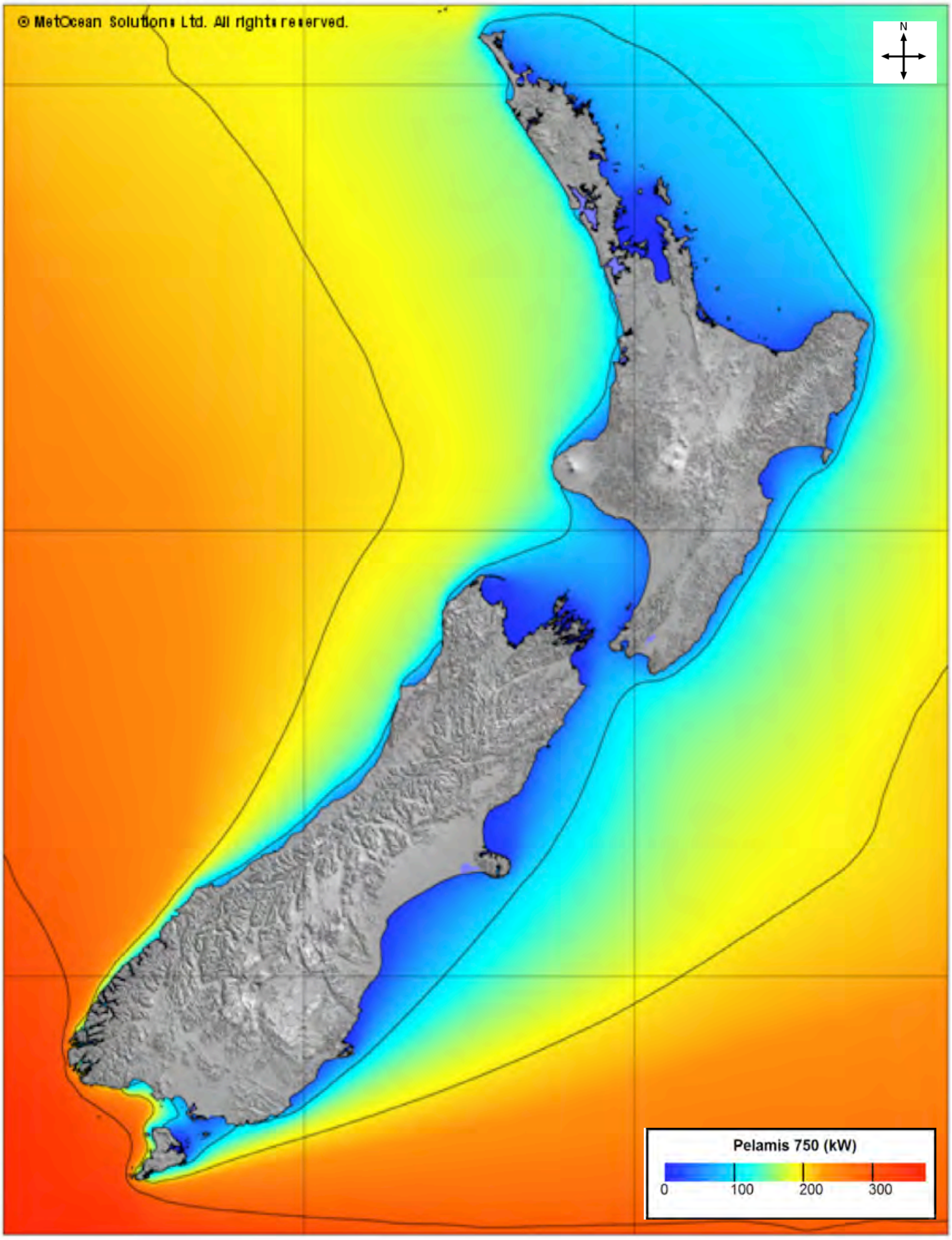


Figure 5.3: Mean Power Output from a 750 kW Pelamis device (1997-2007)

Note: colour scale is specific to this map

Figure 5.3 is the integration of the mean spectral wave power and the power spectrum from the 750 kW Pelamis device (Section 4.2.1). The interpretation of this map is that the contour values (measured in kilowatts) define the mean instantaneous power output from a single 750 kW Pelamis device at any point on the map. A single Pelamis device located off southwest Fiordland would, on average, produce in excess of 300 kW continuously. The same device located just outside the Manukau Harbour would produce an average output of c. 100 kW.

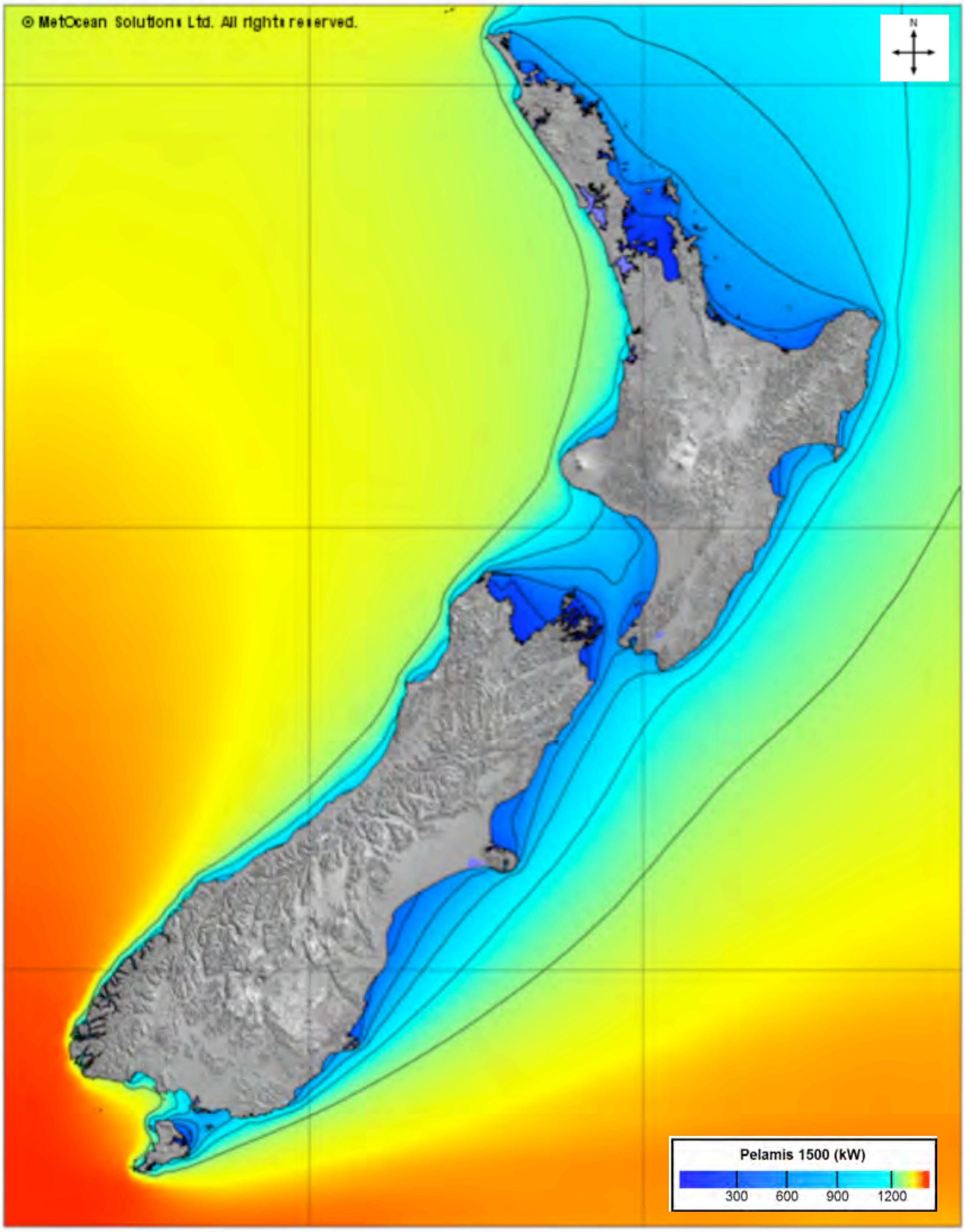


Figure 5.4: Mean Power Output from a 1.5 MW Pelamis device (1997-2007)

Note: colour scale is specific to this map

Figure 5.4 is the integration of the mean spectral wave power and the power spectrum from the scaled-up 1.5 MW Pelamis device (Section 4.2.2). The contour values (measured in kilowatts) define the mean instantaneous power output from a notional 1.5 MW Pelamis device at any point on the map. A single 1.5 MW Pelamis device located off southwest Fiordland would produce an average in excess of 1.3 MW continuously. The same device located just outside the Manukau Harbour would produce an average output of c. 1 MW.

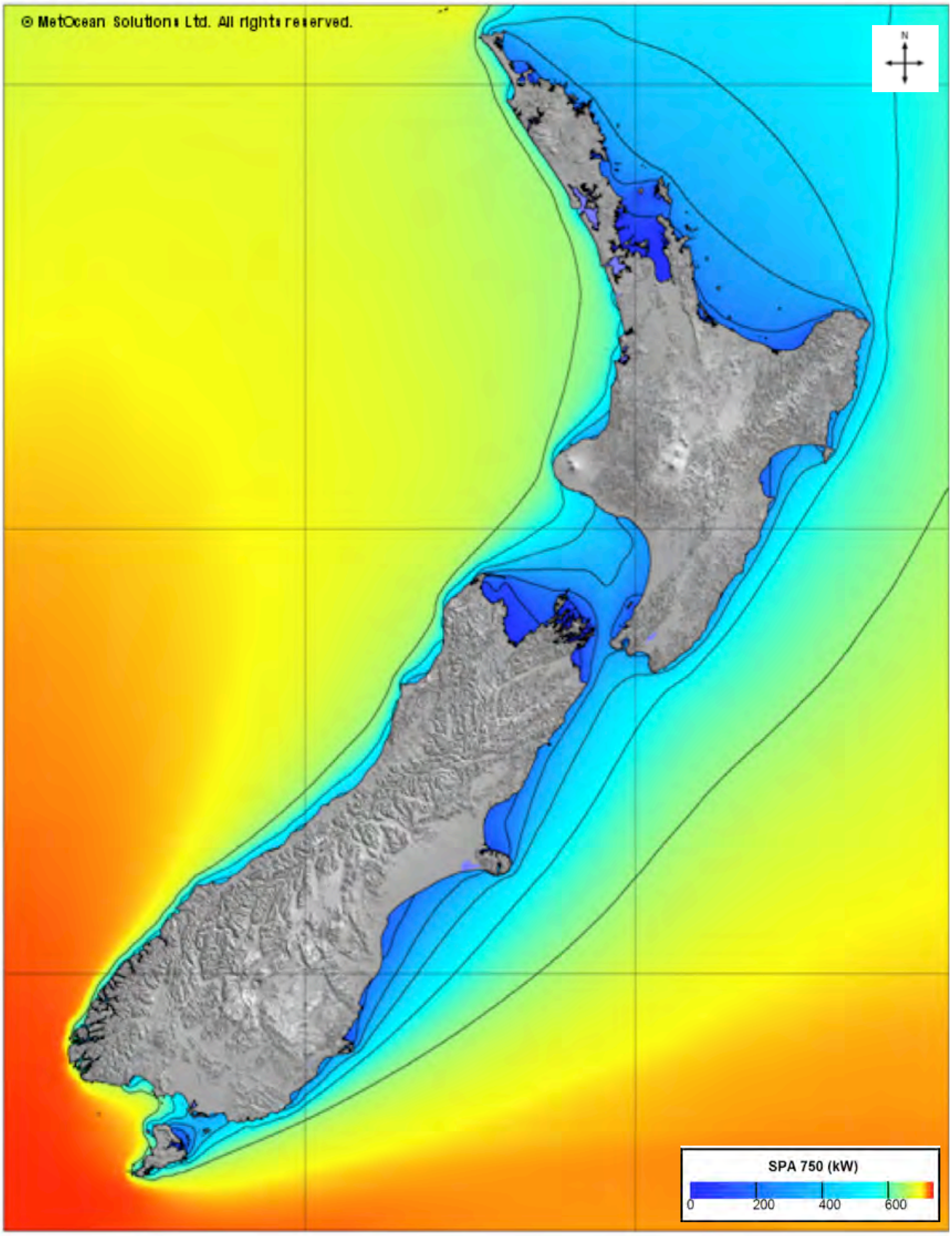


Figure 5.5: Mean Power Output from a 750 kW SPA device (1998-2007)

Note: colour scale is specific to this map

Figure 5.5 is the integration of the mean spectral wave power and the power spectrum from the 750 kW SPA device (Section 4.2.3). The contour values (measured in kilowatts) define the mean instantaneous power output from the SPA device at any point on the map. A single SPA device located off southwest Fiordland would produce an average in excess of 600 kW continuously. The same device located just outside the Manukau Harbour would produce an average output of *c.* 500 kW.

5.2 SPECIFIC WAVE ENERGY SITES

Six sites have been analyzed in detail to assess the potential electricity generation potential of wave device array deployment at each of the sites. The sites were chosen to represent the range of wave climates around New Zealand:

1. All modelled sites were 6 km from the coast, a reasonably small distance for a submarine export cable but sufficiently far offshore not to inconvenience most competing users (*i.e.,* not ordinarily visible from the coastline)
2. Sites had a range of water depths from 23 to 65 m
3. Sites were selected for their proximity to onshore transmission grid/distribution network access and proximity to potential load centres.

The sites chosen were all open-ocean locations offshore from Port Waikato, Taranaki (near Cape Egmont), Gisborne, Wairarapa (near Riversdale), Westport and Southland (near Orepuki) (Figure 5.5).

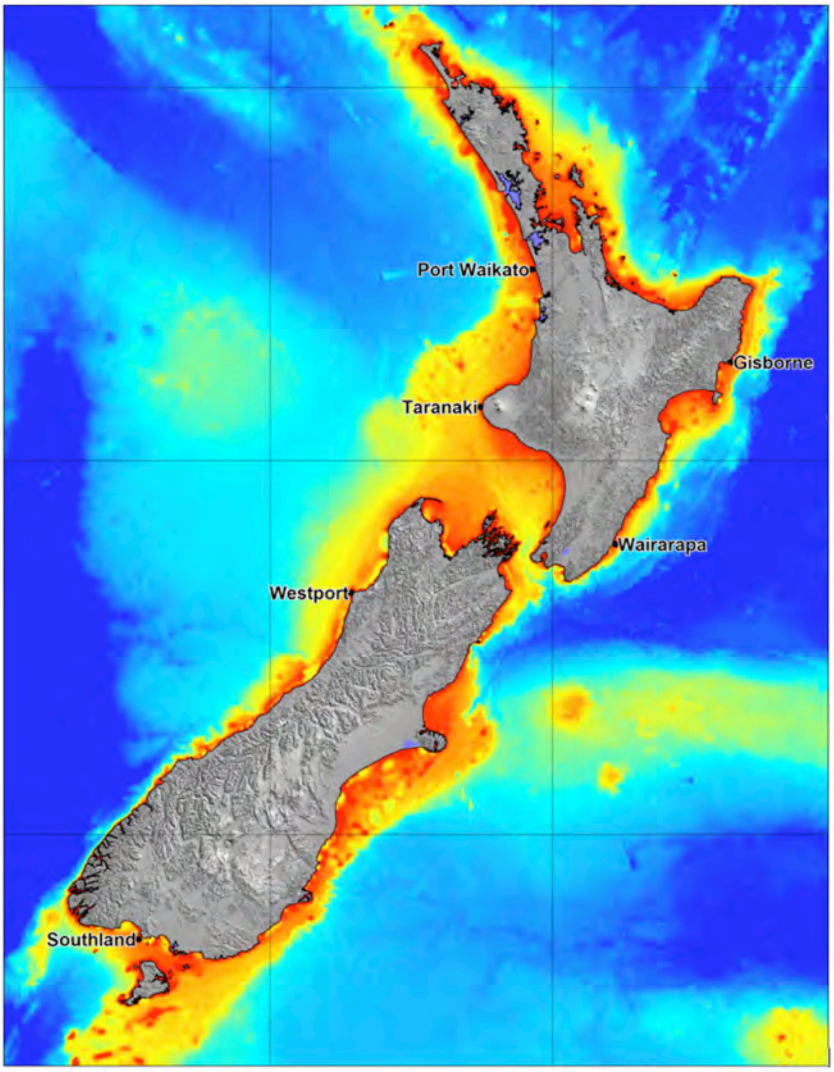


Figure 5.5: Location of Sites of Specific Wave Power Evaluation

5.2.1 Wave Farm Arrays at Selected Sites

Summary statistics of the wave climates at each site have been produced from the wave hindcast data. These statistics have then been used to calculate the annual electricity production from a wave farm array at each site. Each modelled wave device has been applied to each site so that there are eighteen different potential wave farm arrays.

To assess the power output of each wave farm arrays, the following assumptions about the layouts of each of the arrays have been made:

1. Each wave farm will comprise fifty wave energy converters
2. The rated capacity of the arrays of Pelamis P750 and 750 kW SPA devices will be 37.5 MW, whilst the 1.5 MW Pelamis array will be 75 MW.

Keeping the number and capacity of the arrays the same at each site allows a comparison of the space requirements of the arrays at each site (Table 5.1). Clearly, any project developer would determine the capacity and number of devices at any site as part of their economic evaluation of the project.

The density of packing of wave energy devices in an array is an area of active research and the only current array in the world is three CETO II devices moored outside Fremantle Harbour. Carnegie Corporation claims that they will ultimately achieve 8 MW/km^2 for the CETO II device. However, it should be noted that these devices have very low rated capacity, 300 MW, compared with the devices modelled here. The optimal layout and packing density of devices, and wake and other effects between devices are still uncertain. The following assumptions regarding packing density and related effects have been made:

1. 1,500 kW Pelamis packing density: 12.5 per km^2 (Scottish Executive, 2006)
2. Pelamis P750 packing density: 15 per km^2 (scaled, after Scottish Executive, 2006)
3. 750 kW SPA device packing density: 25 per km^2, on the basis that these devices have a much smaller footprint than Pelamis devices.
4. A (pessimistic) power loss of 5% through array effects, although others use a figure of only 1% (Scottish Executive, 2006).
5. The capacity factor (annual mean yield / nameplate capacity) is calculated and not assumed.

Device	Rated Capacity	Sea Room	Packing Density	Generation Density
	MW	Km^2	Devices/km^2	MW/Km^2
Pelamis P750	37.5	3.33	15.0	11.25
1,500 kW Pelamis	75.0	4.00	12.5	18.75
750 kW SPA	37.5	2.00	25.0	18.75

Table 5.1: Proposed Wave Farm Arrays

Combining these array designs with the power production for single devices, calculated from the modelling, enables an assessment of the annual yield (in MW), annual production (in GWh/year) and the capacity factor of each array.

For an array of Pelamis 750 devices, production is relatively low. This is because individual devices never achieve their rated 750 kW capacity, even at the most energetic location in Southland (Unit Power column, Table 5.2). As a result annual mean yields are substantially lower than the 37.5 MW nameplate capacity. More tellingly, the calculated capacity factor is low and very low in the more sheltered locations (11 – 29%). These are very modest values, since the calculations have not assumed any availability factor – the devices are continuously available. However, the evaluation is based upon the device developer's published power spectrum and, for that reason, is regarded as reliable.

Location	Unit Power	Array Capacity	Annual Mean Yield	Capacity Factor	Annual Production
	kW/unit	50 x 750 kW	MW/year	%	GWh/year
Port Waikato	129	37.5	6.1	16	53.7
Taranaki	149	37.5	7.1	19	62.0
Gisborne	88	37.5	4.2	11	36.6
Wairarapa	109	37.5	5.2	14	45.4
Westport	158	37.5	7.5	20	65.7
Southland	228	37.5	10.8	29	94.9

Table 5.2: Annual Production from a 50 x Pelamis P750 Array

By contrast the power produced by an array of 50 of the modelled 1,500 kW Pelamis device is very high. Annual mean yields are in the range 38.7 to 64.3 MW *per annum* (Table 5.3). Capacity factors are therefore very high (52 – 86%), probably unrealistically high. Even if an availability factor (85 - 95%; EPRI, 2003) were included in the calculation, it would be unlikely to reduce capacity factors to the figures of between 20% and 40% cited or assumed in other analyses (*e.g.,* EPRI, 2003). The likely source of the over-estimation error is the modelled power spectrum, which effectively allows the modelled device to generate high levels of power in a wide range of conditions.

Location	Unit Power	Array Capacity	Annual Mean Yield	Capacity Factor	Annual Array Production
	kW/unit	50 x 1,500 kW	MW/year	%	GWh/year
Port Waikato	1,236	75.0	58.7	78	514.3
Taranaki	1,275	75.0	60.6	81	530.5
Gisborne	815	75.0	38.7	52	339.1
Wairarapa	999	75.0	47.4	63	415.7
Westport	1,316	75.0	62.5	83	547.6
Southland	1,354	75.0	64.3	86	563.4

Table 5.3: Annual Production from a 50 x 1,500 kW Pelamis Array

The power output from an array of 50 x 750 kW SPA devices has a range of annual mean yields between 17.6 and 30.5 MW per annum (Table 5.4). This yield translates to a range of capacity factors between 47% and 81%. Though more moderate than the figures for the 1,500 kW Pelamis array, these capacity factors are still much higher than would be expected. Again, source of the over-estimate is most likely the modelled power spectrum derived for this device.

Location	Unit Power	Array Capacity	Annual Mean Yield	Capacity Factor	Annual Array Production
	kW/unit	50 x 750 kW	MW/year	%	MWh/year
Port Waikato	551	37.5	26.2	70	229.3
Taranaki	572	37.5	27.2	72	238.0
Gisborne	371	37.5	17.6	47	154.4
Wairarapa	441	37.5	21.0	56	183.5
Westport	592	37.5	28.1	75	246.3
Southland	643	37.5	30.5	81	267.6

Table 5.4: Annual Production from a 50 x 750 kW SPA Array

5.2.2 Summary of Wave Device Array Locations

Wave spectra derived from 10-year hindcasts have been integrated with model power spectra for three generic device types. Some significant conclusions emerge from the calculation of output power from arrays of fifty of the devices:

1. Regardless of the selection of the device, the six locations produce unit power in the same order: Southland, Westport, Taranaki, Port Waikato, Wairarapa and Gisborne. Clearly, choice of location is the critical factor in likely power production.
2. Modelled arrays at Southland, Westport, Taranaki and Port Taranaki produce comparative amounts of power, whilst the Wairarapa and Gisborne produce less but remain potential sites.
3. Not surprisingly, the larger the capacity of devices, the higher the unit power output. The 1.5 MW unit generators produce substantially more power than the 750 kW devices.
4. The 750 kW attenuator devices produce between one-quarter and one-third of the power of the point absorber devices and between one-tenth and one-sixth of the output power of the 1.5 MW attenuator devices. This is the result of the 750 kW attenuator devices rarely achieving their peak output. They perform best in more energetic conditions, which rarely occur.
5. The 1.5 MW devices generate approximately 100% more unit power at the Southland location than they would at the Gisborne location
6. The 750 kW point absorber devices generate about 73% more power at Southland compared with the Gisborne location.
7. The 750 MW attenuator devices generate 150% more power at the Southland location than at Gisborne but overall production is low.
8. The 1.5 MW attenuators and 750 kW devices extract a greater proportion of energy in normal, rather than extreme conditions.

Note that the conclusions here are based on modelled power spectra and the results are valuable for comparative, rather than absolute, purposes. The very high (and probably unrealistic) capacity factors calculated from this analysis indicates that further work is required to refine the analysis. Improved power spectra, based on real performance measurements, would enable more reliable estimates of power output but device developers do not routinely make these publicly available.

The analysis does show that the characteristics of the wave conditions at each site have significant effects on the output power, whilst the selection of device types is key decision in determining the likely power production from each array. Selection of device type would be critical in the less productive east coast locations but device survival (and capacity factor) are likely to be bigger issues at the more energetic locations.

5.3 TIDAL & OCEAN CURRENT ENERGY POTENTIAL LOCATIONS

The maps presented in this section are the depth-averaged mean Spring tidal flows, derived by combined the principal lunar semidiurnal constituent (M2) with the S2 solar constituent. This is a good approximation of the mean of the highest flows that occur on a monthly basis.

There are two '*rules of thumb*', which will assist an understanding and evaluation of the maps of the tidal resource in following sections:

1. All in-stream tidal devices have a '*cut-In speed*', the point at which the turbines will self-start and begin to generate power. A current speed of 0.7 m/sec is generally considered the cut-in speed for most horizontal axis in-stream current devices (Scottish Executive, 2006).
2. However, mean tidal current speeds of less than 2 m/sec are unlikely to contain much power and would be unlikely to support deployment projects at the current state of technological development. A nominal minimum figure of 1 m/sec is required to be attractive for potential deployments.

5.3.1 National & Regional Distribution of Potential Locations

Mapping shows that the depth-averaged current speeds for mean Spring flows over most of the New Zealand CMA (and Exclusive Economic Zone) are very low, *c.* 0.3 (Figure 5.6). Since the cut-in speed of in-stream turbines is about 0.7 m/secs, there are clearly few places, where tidal/ocean current projects will be possible.

The map does show that there are three open ocean areas of interest, namely:

1. Cape Reinga
2. Cook Strait
3. Foveaux Strait & south side of Stewart Island

At this regional scale of mapping, the well-known localised areas of tidal current flow are not resolved. Locations such as French Pass and Tory Channel in the Marlborough Sounds, and the large harbour and estuarine environments in the North Island (e.g. Kaipara Harbour) do offer a potential tidal resource, albeit with a more limited spatial extent (Bellve *et al.,* 2008). However, these locations fall beyond the scope of the present report, which considers the open-ocean resources only.

Note that the North Island west coast harbours have not been modelled and mapped in detail, because they would require detailed bathymetric data. As we shall see, the largest, the Kaipara Harbour, is already subject of consent applications for a tidal current project (Section 6.2.2), which may limit the opportunity for other developers.

Cape Reinga was not studied in detail and is not considered further in this report, because there is a clear lack of transmission and distribution infrastructure at the northern tip of the Northland peninsula. It is also a considerable distance north of any significant population or load centres.

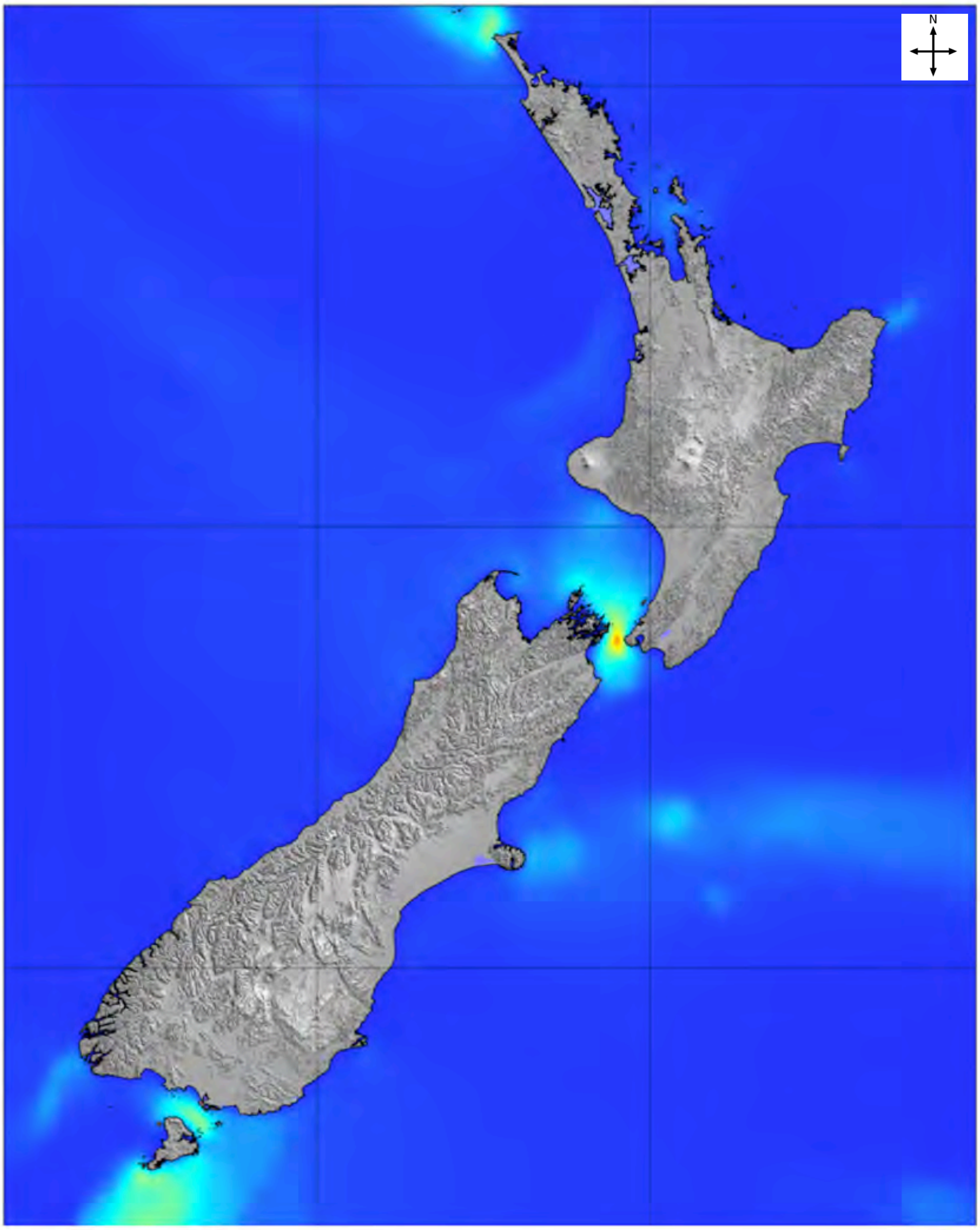


Figure 5.6: Depth-averaged Tidal Current Speeds for Mean Springs Flows

5.4 SPECIFIC TIDAL & OCEAN CURRENT SITES

The national mapping clearly indicates that the eastern side of Cook Strait, Foveaux Strait and south of Stewart Island offer the best opportunities in terms of the mean current velocities from the modelling. These areas were subject to more detailed modelling and six sites, five on the eastern side of Cook Strait (Figure 5.8). One promising site in Foveaux Strait south of Bluff was selected for detailed evaluation (Figure 5.9). All six were analyzed, using the modelled in-stream turbines

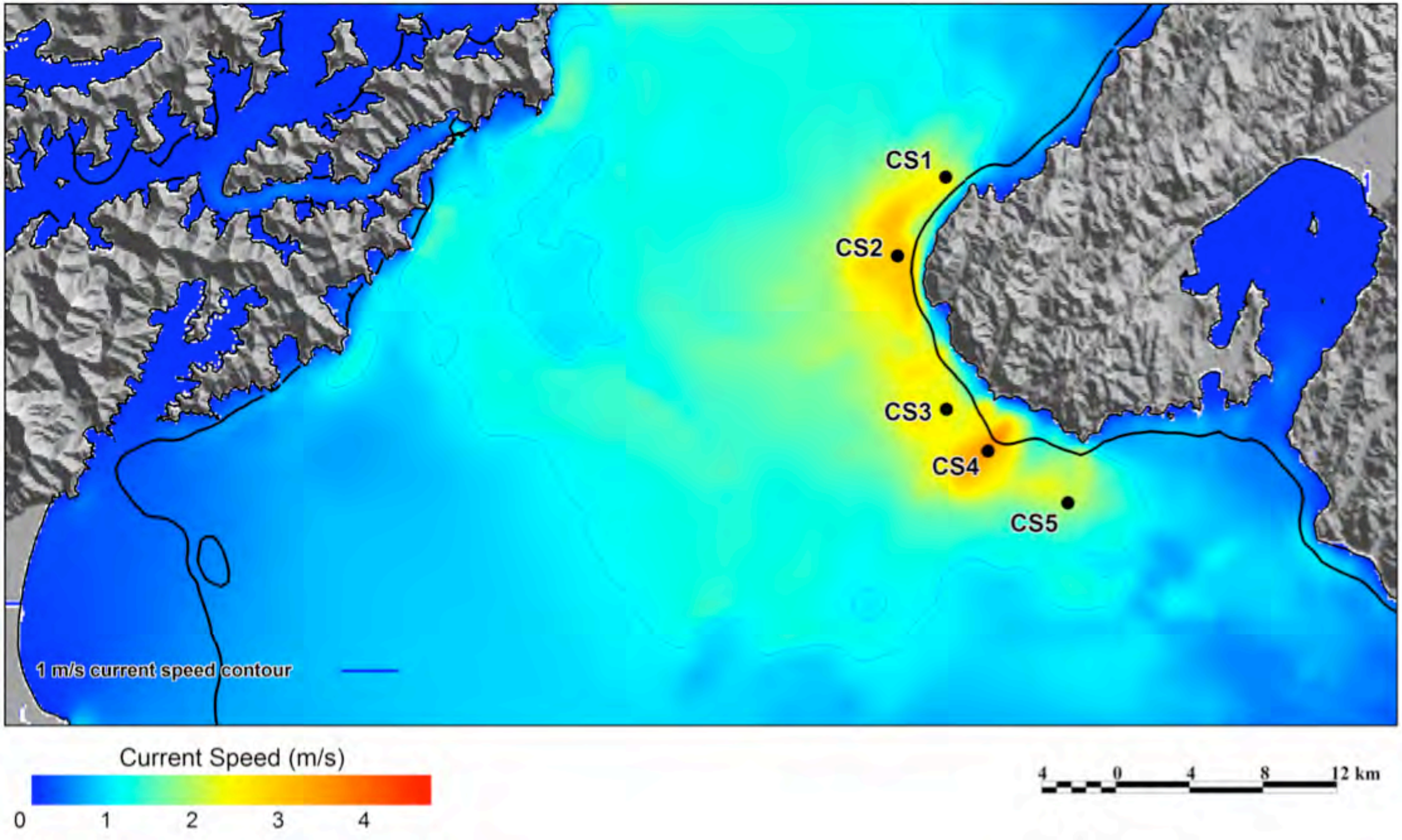


Figure 5.7: Selected Modelling Locations in Cook Strait

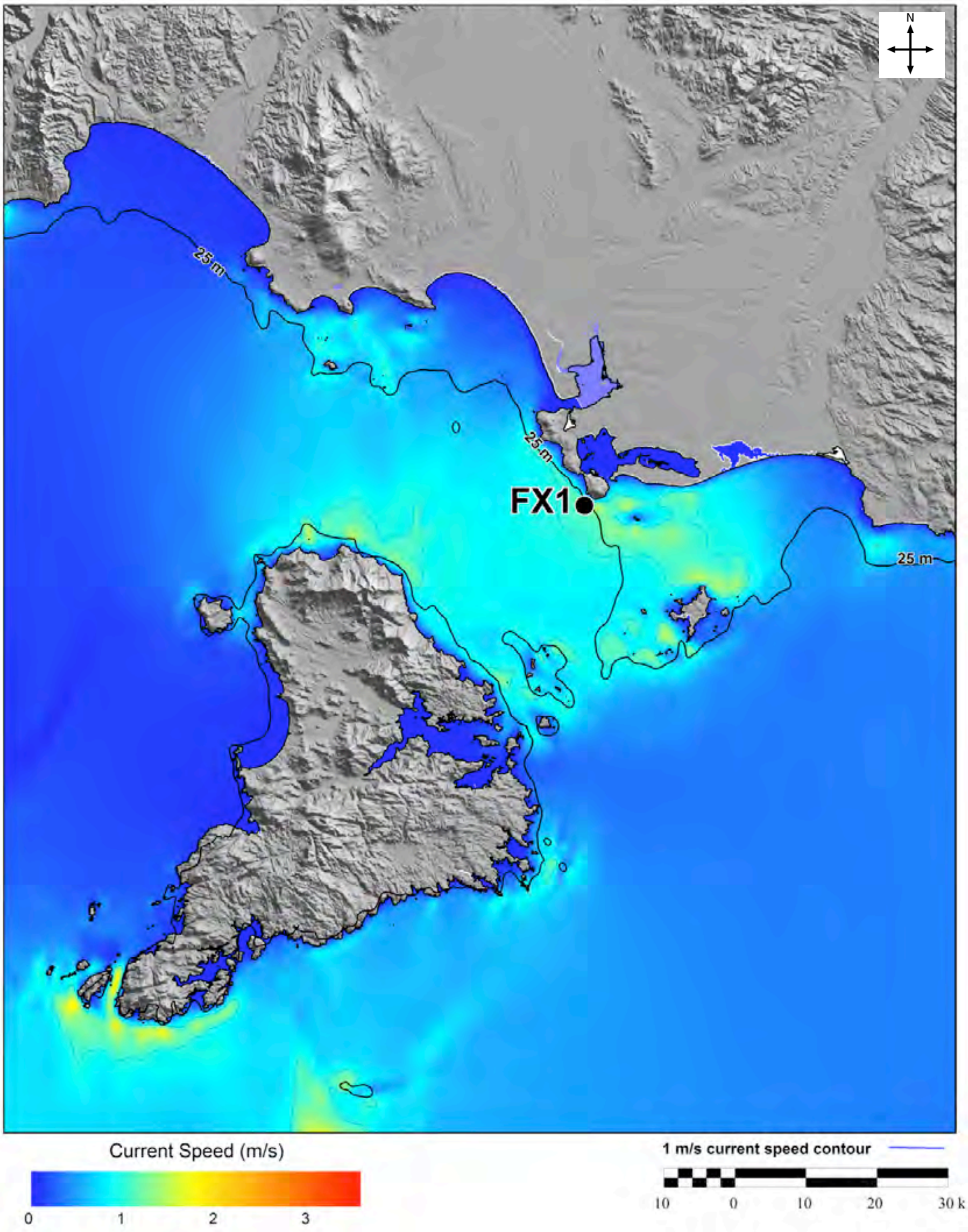


Figure 5.8: Selected Modelling Location in Foveaux Strait

5.4.1 Southland

Detailed mapping of the Southland region shows that there are three areas of increased tidal/ocean current flows: the south side of the Bluff peninsula and the northern and southern tips of Stewart Island (Figure 5.9). These last two are interesting but of relatively little potential since they are some distance from infrastructure or population. The area south of Bluff is a very attractive location – close to the coast and approximately 6 kilometres from the Tiwai aluminium smelter. The five sites within Cook Strait, which were analyzed, are also described here.

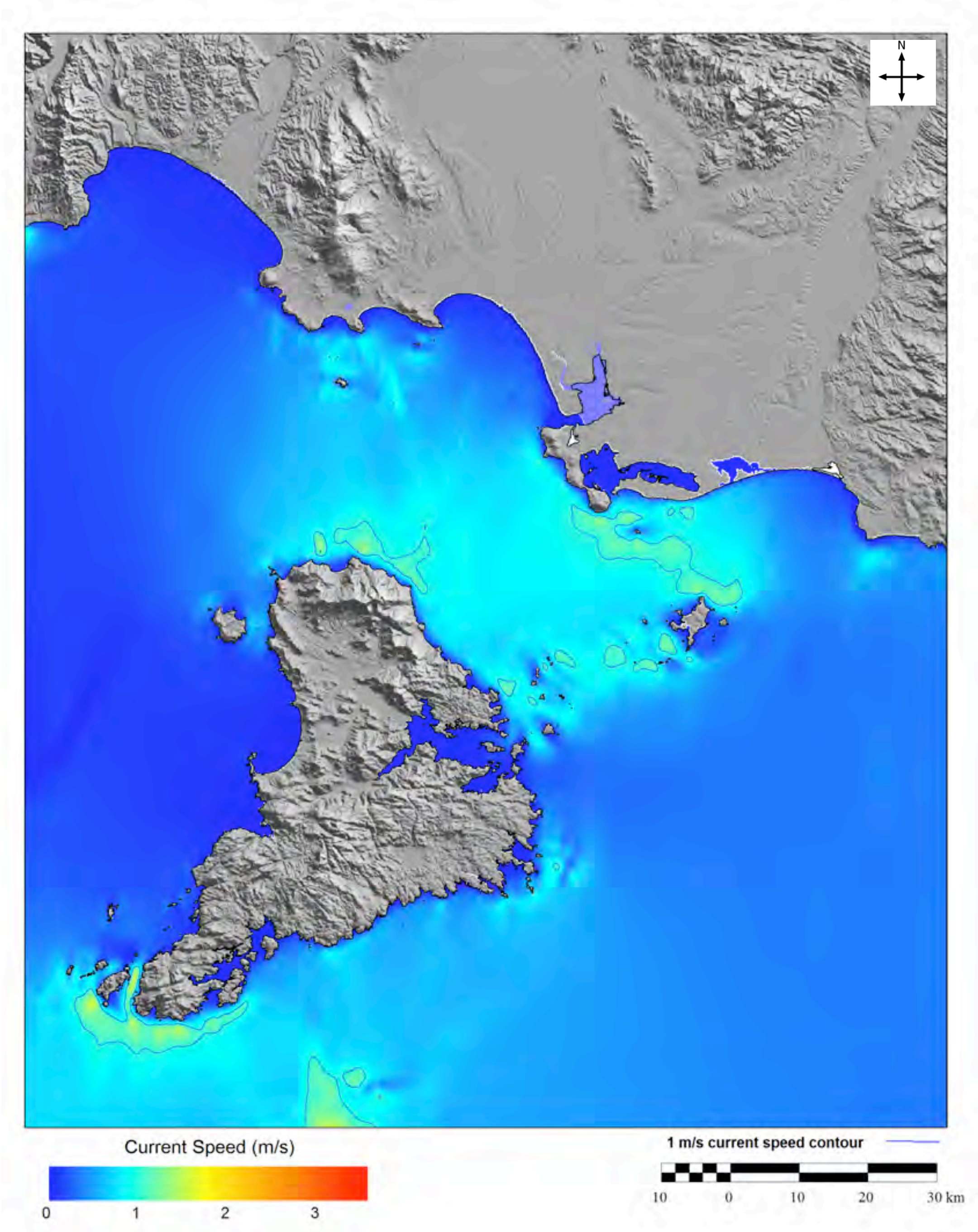


Figure 5.9: Depth-averaged Tidal Current Speeds for Mean Springs for Southland

Note: contour shown is 1 m/second speed contour

5.4.2 Tidal/Ocean Current Arrays in Foveaux Strait and Cook Strait

As with the wave energy sites, six sites have been analyzed in detail to assess the potential generation from deployments of tidal/ocean current device arrays. The sites were chosen to represent the range of tidal/ocean current conditions in two areas: Cook Strait and Foveaux Strait (Figure 5.8).

Some assumptions have been made about the layout of each of the nominal arrays to enable an assessment and comparison of the power output of the arrays at each site. For the purposes of this analysis, each array has been designed as follows:

1. Array comprises fifty tidal/ocean energy converters
2. The rated capacities of 50 x 300 kW SeaFlow device arrays (15 MW), and
3. The rated capacities of 50 x 1.2 MW SeaGen device arrays (60 MW)

The density of packing of the tidal/ocean current arrays is also a subject of active research. The only in-stream array recently in operation is that of Verdant Power in the East River, New York. However, these devices are relatively small (35 kW units) and are not directly comparable with 1.2 MW units, such as SeaGen. Packing densities in the literature range widely between 15 units/km^2 (Scottish Executive, 2006) to 200 units/km^2 (EPRI, 2003).

The EPRI figure, based upon 18 m diameter turbines and using separation distances extrapolated from experience with wind turbines - namely lateral spacing of 9 m and downstream spacing of 180 m (10 rotor diameters), uses a technique that accounts only for the influence of neighbouring turbines upon others within the array. This approach can often over-estimate the achievable packing density, as it takes no account of the actual energy flux incident upon the array, *i.e.,* it is possible to conceive of an array that captures more energy than is actually available.

The amount of extractable energy at a particular tidal site is a contestable issue that is receiving attention within academia. The Significant Impact Factor (SIF) is an estimate of the fraction of the energy in a particular site that can be extracted, without altering the underlying hydrodynamic characteristics of the site. Some authors (*e.g.,* Couch & Bryden, 2004) estimate the SIF at 10%, whereas others (*e.g.,* Salter, 2005) suggest that it could be significantly higher. The Carbon Trust (Carbon Trust, 2005) suggests a range of 10 - 50% and emphasizes that it will be unique to a particular site.

A spacing model developed by the Energy Systems Research Unit of the University of Strathclyde), taking into account the SIF, indicates a lateral spacing of 60 m and longitudinal spacing of 250 – 1,000 m (Strathclyde University, 2008. This suggests a narrower range of packing densities - between 12 and 48 units per km^2.

The conservative figure of 15 units/km^2 has been selected here but further research on this subject is required.

There are also serious wake effects, caused by turbulence created by the devices and this is also an area of active research. Two assumptions have been made:

1. A capacity factor of 40% has been assumed for both devices
2. A power loss of 5% due to wake effects has been used (Scottish Executive, 2006)
3. Both devices have a packing density of 15 units/km^2

The design of the arrays of the two devices is shown in Table 5.5.

Device	Rated Capacity	Packing Density	Sea Room
	MW	Devices/km^2	Km^2
300 kW SeaFlow	15.0	15.0	3.33
1.2 MW SeaGen	60.0	15.0	3.33

Table 5.5: Proposed Tidal/Ocean Current Arrays

Combining the array design and power production for the SeaFlow device enables an assessment of the annual yield in MW and annual production at each site (Table 5.6).

Location	Water Depth	Unit Power	Array Capacity	Annual Mean Yield	Annual Production
Figures 5.8 & 5.9	m	kW/unit	50 x 300 kW	MW/year	GWh/year
CS1	42	48.8	15.0	2.32	20.3
CS2	50	93.4	15.0	4.44	38.9
CS3	69	49.6	15.0	2.36	20.6
CS4	31	107.2	15.0	5.09	44.6
CS5	86	33.0	15.0	1.57	13.7
FX1	31	8.5	15.0	0.40	3.5

Table 5.6: Proposed 50 x 300 kW Seaflow Tidal Current Arrays

Similarly, combining the SeaGen device power production with the array parameters for a 50-unit array and convolving them with the resource characteristics at the six sites yields a wide range of results in terms of annual yield in MW/year and annual production GWh/year (Table 5.7).

Location	Water Depth	Unit Power	Array Capacity	Annual Mean Yield	Annual Production
Figures 5.8 & 5.9	m	kW/unit	50 x 1.2 MW	MW/year	GWh/year
CS1	42	210.0	60.0	9.98	87.4
CS2	50	400.0	60.0	19.00	166.4
CS3	69	211.0	60.0	10.02	87.6
CS4	31	458.6	60.0	21.78	190.8
CS5	86	143.0	60.0	6.79	59.5
FX1	31	38.8	60.0	1.84	16.1

Table 5.7: Proposed 50 x 1.2 MW SeaGen Tidal Current Arrays

The tables clearly show that the Cook Strait arrays produce significantly more power than the Foveaux Strait array, which probably reflects the relatively low current speed at and small area of the Foveaux Strait site. Amongst the Cook Strait sites, CS2 and CS4 are clearly much more productive than the other sites. Inspection of the maps confirms that these sites have the highest current speeds and largest areal extent.

The sites are somewhat areally restricted and the shoreward extensions of the areas may be too shallow for larger turbines. A detailed study of each site would identify the potential locations for turbines and thus the practical capacity at each site.

5.4.3 Summary of Tidal/Ocean Current Device Array Sites

Power spectra from two generic tidal/ocean current devices have been integrated with 10-year hindcasts of current flows from six locations in Cook Strait and Foveaux Strait. Unit power, annual mean yield and annual power production have been determined for 50-unit arrays of two generic devices at each site. Some significant conclusions emerge from the calculation of power outputs from the modelled arrays:

1. Output power varies considerably for each of the devices at each site. There is about 13 times difference between the power output of the arrays at the most energetic site (CS4), compared with the least energy sites modelled here (CS4). Mean velocities at each site are a critical factor in determining the output from arrays at each site.
2. Regardless of the selection of the device, the six locations produce unit power in the same order: CS4, CS2, CS3, CS1, CS5 and FX1. The choice of location is the critical factor in likely power output.
3. There is an obvious correlation between the sites with the highest mean velocities and the power output from arrays at each site – compare CS2 and CS4 with the other Cook Strait sites in Figure 5.8.
4. The proposed location of the Neptune Power prototype turbine is coincident with the weakest current location in this study – a good choice for a first deployment. It would not be the preferred location for a commercial deployment, when compared with the other Cook Strait locations.
5. The Foveaux Strait location is much less productive than all the Cook Strait locations but this is a logical conclusion from the lower mean current velocity modelled at the site (compare Figure 5.8 and 5.9).
6. The larger 1.2 MW device array produces about 4 times more annual electricity than the 300 kW device array. This is partly because the 1.2 MW device is a twin-turbine device and also because the larger diameter blades (16 m *versus* 10 m) have more than double the swept area.

PART 6: GROWTH OF THE MARINE ENERGY INDUSTRY

6.1 INTERNATIONAL GROWTH

6.1.1 International Forecasts for Marine Energy Development

In 2006 the British Wind Energy Association – despite its name, the UK trade association for marine energy – produced the "*Path to Power*", a policy review document seeking to promote marine energy in the United Kingdom (BWEA, 2006). The analysis undertaken for this study, undertaken in 2005, was based upon scenarios forecasting the deployment of prototype devices (*c*. 1 MW), small arrays (*c*. 5 MW), large arrays (*c*. 30 MW) and, in due course, significant projects (>30 MW).

The results of the study indicated that the UK could potentially achieve marine energy deployments totalling 3,000 MW by 2020. This assessment now looks too optimistic. Present deployments in the UK are a long way short of the cumulative total (50 MW) forecast for 2008 in the study (Figure 6.1). It also seems unlikely that the UK will achieve a total of about 220 MW by 2012, even if the EMEC and Wave Hub facilities are fully occupied by this time.

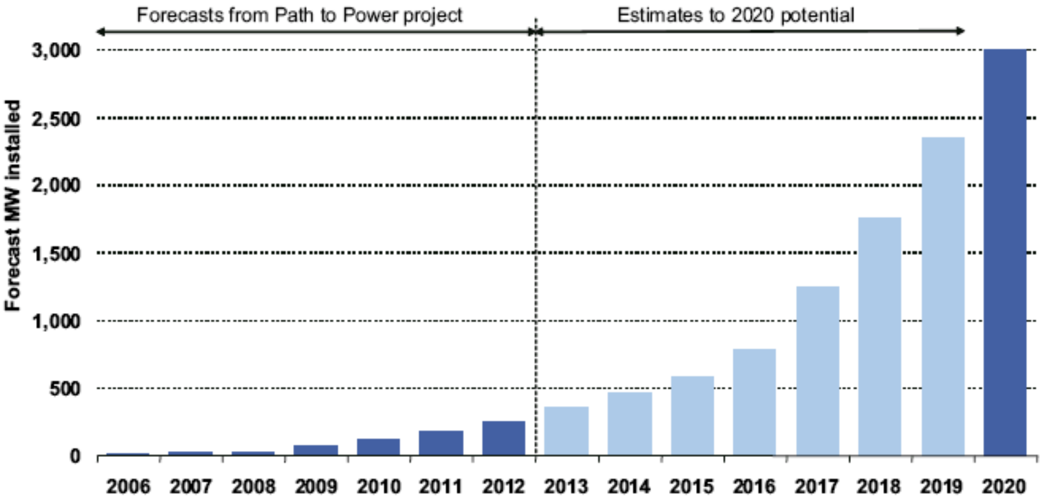


Figure 6.1: Marine Energy Uptake Forecast for United Kingdom (BWEA, 2006)

Just prior to the BWEA study, the Scottish Executive attempted to forecast the development of marine energy both within Scotland and worldwide (Scottish Executive, 2005). The analysis indicated very slow growth in the early 2000s but a Figure 6.2). Almost 50% of the capacity growth was forecast to occur in the United Kingdom and the growth of wave energy capacity was forecast to be about 60% of the total. By 2009 the Scottish Executive expected marine energy capacity to reach a cumulative total of 84 MW.

In the event, deployments of marine energy have been slower than forecast, although it is true that the UK has had the highest proportion of deployments and there have been more wave than tidal deployments. At the end of 2007 the cumulative total of deployed capacity (not including devices which had been previously deployed and subsequently removed or become non-operational) was 8 MW (IEA:OES, 2008). This figure will rise later this year due to:

1. Deployment of Marine Current Turbines' 1.2 MW SeaGen tidal stream turbine (Section 2.3.5), and
2. Belated deployment of the three Pelamis devices at Aguçadoura in Portugal (Carcas, 2008).

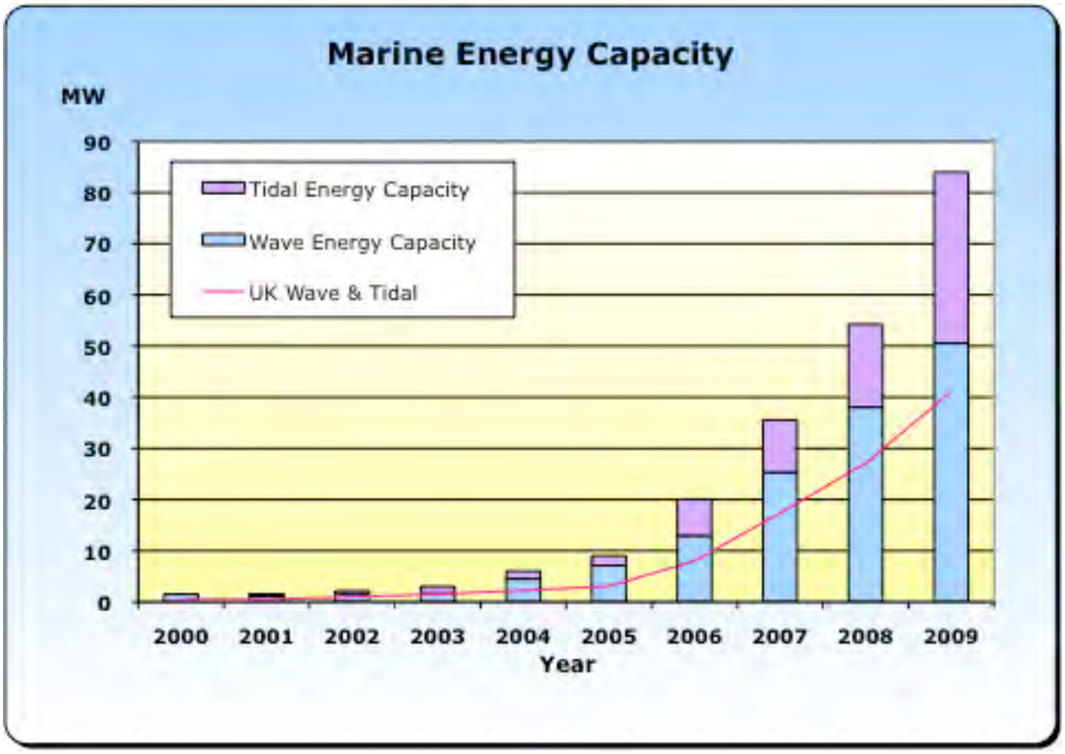


Figure 6.2: Forecast Worldwide Marine Energy Capacity Growth (SE, 2005)

Nonetheless, the total capacity of marine energy deployed and operational at the end of 2008 will not be close to the 54 MW figure forecast by Scottish Executive (SE) in 2004. Worldwide deployments are lagging the SE estimates by about 3 years.

Part of the reason for the lag of deployments is over-optimistic development timetables for device developments. A recent study in the UK has shown that device developments tend to more complex than developers envisage (RAB, 2008). Delays are caused because:

1. Prototype developments take longer than expected
2. By and large, each device is being developed in isolation and there appears to be little collaboration and pooling of ideas
3. Unexpected events cause significant delays
4. Supply chain capacity is quickly exceeded, so equipment or materials are not readily available.

Delays in UK-based projects since 2000 have averaged at least two years and over eight years in one case.

Whilst the absolute figures may be over-estimated, the general trend is probably reasonable (and similar to wind energy, see below). The increasing rate of device deployments is driven by a number of factors:

1. A number of relative new companies have moved from start-up to device deployments very quickly (*e.g.,* OpenHydro: founded in 2005, first deployment of a 250 kW generator in 2008).
2. Over the last few years some device developers have announced multiple projects, even though they have yet to develop and deploy a mature technology (Table 6.1).

3. Device developers are planning multi-device arrays as their principal mode of commercial deployment. Deployments, although constructed incrementally, will be built on a utility scale.

Device developers are signing contracts for multiple international projects, securing access to multiple sources of funding and supply chains, so that finance and fabrication capacity are unlikely to be significant brakes on development in future. The implication is that once developers can deploy a mature technology, the next phase of growth of marine energy will be very rapid - only slowed by developers' capacity to secure planning consents for deployment and to build multiple machines. Taking a representative sample only, six of the more advanced device developers have publicized projects at 21 locations, which could increase international marine energy capacity by 634 MW by 2015. (There is little point trying to devise a comprehensive listing, because many developers are commercially sensitive and secretive about their plans, new devices may become available in the period to 2015 and there is no guarantee that the projects listed will proceed as proposed).

Developer	Projects		
	Location	Capacity (MW)	Details
Pelamis	Aguçadoura, Portugal	22.5	3 x 750 kW Option to add 20 MW
	Orcadian Wave Farm	3.0	4 x 750 kW
	WestWave, Cornwall	5.0	Up to 7 x 750 kW
Ocean Power Technologies	Atlantic City	0.04	40 kW prototype
	Hawaii	1.0	Multi-unit array planned
	Santoña, Spain	1.4	Multi-unit array planned
	Perth, Australia	100.0	10 MW array to grow to 100 MW
Finavera (AquaBuOY)	Makah Bay, Washington	1.0	1 MW demonstration plant deployed
	Coos County, Oregon	100.0	FERC preliminary permit received
	Ucluelet, B. Columbia	5.0	Investigative Use permit granted
	Western Cape, South Africa	20.0	Multi-unit array
Oceanlinx	Port Kembla, NSW	0.45	450 kW prototype
	Portland, Victoria	27.5	Multi-unit array planned
	Rhode Island	21.5	1.5 MW unit to be installed with 15-20 MW to follow
	WaveHub, Cornwall	5.0	5 MW array
	Namibia	16.5	1.5 MW to be followed by 10 x 1.5 MW units
	Hawaii	2.7	3 x 0.9 MW units
Lunar Energy	Republic of Korea	300.0	1 MW demonstration, followed by 300 MW array by 2015
OpenHydro	EMEC, Orkney Islands	0.5	Prototype (250 kW) in place and second device planned
	Bay of Fundy, Nova Scotia	1.0	1 x 1 MW unit under construction
	Alderney, Channel Islands	??	Multi-unit array (? x 1 MW units)
6 Developers	**21 Locations**	**634.1 MW**	**Nominal date: 2015**

Table 6.1: Examples of Device Developers with Multiple International Projects

Note: Rather than being exhaustive, this listing merely demonstrates the scale of planned developments by only 6 developers

6.1.2 Comparison with Growth of the Wind Industry

The growth of the international and domestic wind industry offers an insight into how the marine energy industry may develop. Internationally, the wind industry grew steadily once the monopole tower, 3-bladed upwind turbine became the *de facto* standard in the 1980s. However, growth became exponential in the late 1990s and 2000s as wind turbine prices dropped and the unit cost of electricity became competitive with gas- and hydro-generated electricity (WWEA; Figure 6.3). Subsidies, such as feed-in tariffs, which were introduced in Spain and Germany as incentives to encourage uptake of wind (and other forms of renewable energy), have also accelerated uptake.

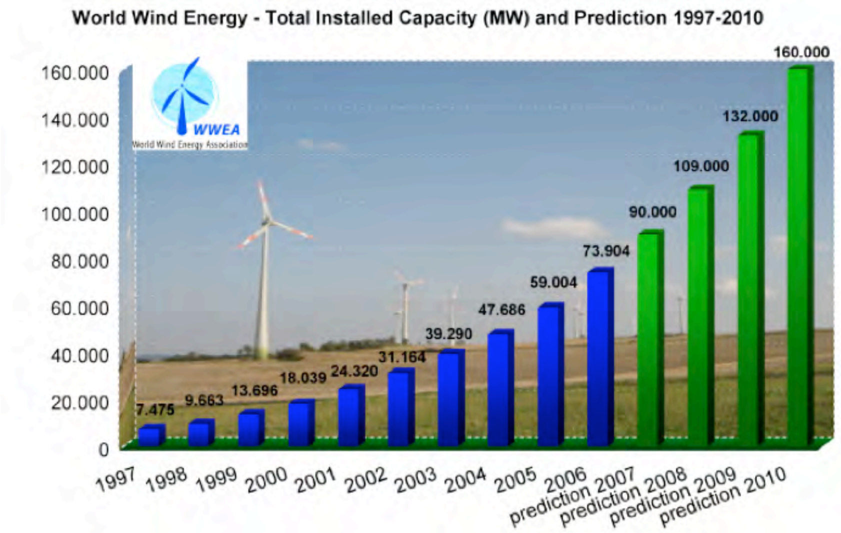


Figure 6.3: International Growth in Wind Energy Capacity (WWEA)

In 2000 global wind energy capacity was 18 GW; the forecast for 2010 is 160 GW – an almost nine-fold increase in 10 years.

In New Zealand the growth of the wind industry was similarly slow to start but since 2004 has been even faster than the international rates (Figure 6.4).

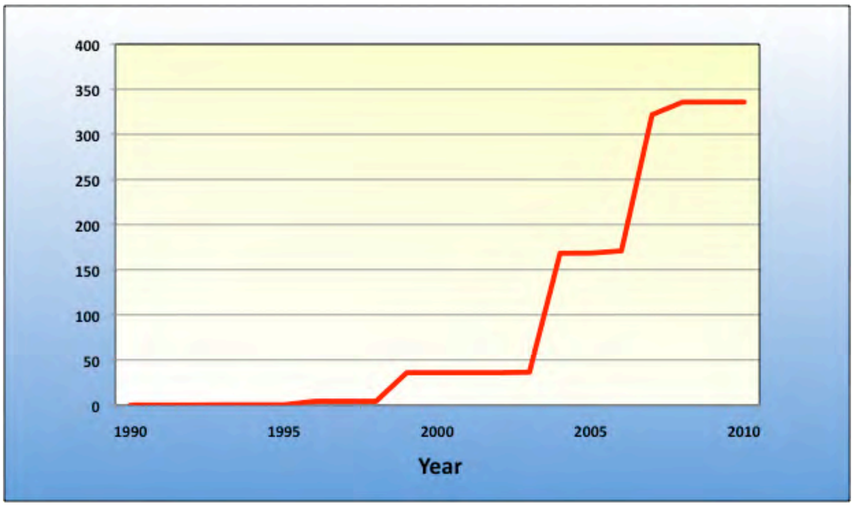


Figure 6.4: Growth of Wind Energy Capacity in New Zealand (Clark, 2008)

Note: the notchy nature of above curve is because developments are shown in the year they were commissioned

In New Zealand the first 250 kW wind turbine generator was installed at Brooklyn in 1993, before the first 3.6 MW wind farm at Hau Nui in Wairarapa was commissioned in 1996 (Clark, 2008). It was another four years before the second wind farm, Tararua I (31.7 MW) became operational and 2004 before the first major wind farm, Te Apiti (90.8 MW), provided power to the National Grid.

At the end of 2006, total domestic capacity was 160 MW but that doubled to 322 MW at the end of 2007. A further 165 MW of capacity under is construction and due to be commissioned in 2008 - 2009. Future growth is likely to be significant with 1,985 MW seeking or granted consents to build (NZWEA, 2008). Wind energy capacity is forecast to grow at between 150 MW and 200 MW per annum for the foreseeable future (Clark, *pers. comm.*).

6.2 STATUS OF MARINE ENERGY IN NEW ZEALAND

6.2.1 Domestic Deployment Projects

Power Projects Limited is aware of at least 24 domestic marine energy projects that have been proposed in the last four years. This is almost certainly an under-estimate because project and device developers tend to work in secrecy. Six of the projects do not involve deployment of devices and not all of the remaining 18 projects are still active. The projects range from conceptual ideas to university research projects to deployment projects like the WET-NZ R & D programme.

Of the 18 device projects, only six have been made public and can be discussed here (Table 6.2). The 18 comprise six wave device projects and 12 tidal device projects and they are evenly balanced between device developments and projects proposing to import overseas technologies. All of these projects were in existence before the Marine Energy Deployment Fund was announced but few would be ready to apply for funding.

Name	Participants	Device/Site	Funding	Comment
Crest Energy	Crest Energy	Open Hydro; formerly Lunar Energy device Kaipara Harbour	Self-funded at present with MEDF funding to come	Resource consents hearings held 29 May 2008
Neptune Power	Neptune Power	TidEL device originally; new device with TNEI Cook Strait	Self-funded at present	Resource consent granted on 10 April 2008
Power Generation Projects	Power Generation Projects	Pelamis importation & domestic fabrication	Self-funded; HERA contributed to UK visit in 2007	Project dormant since UK visit in June 2007
WET-NZ	IRL, NIWA and PPL	WET-NZ's own device; Pegasus Bay & Wellington	Government funding through FRST	Device deployed since Dec 2006; further funding requested
Tidal Flow Seamills	Tidal Flow Seamills	Own vertical axis turbine; Karori Rip	Unknown	Project dormant for at least one year
Natural Systems Limited	Natural Systems Limited	HydroVenturi: Canterbury irrigation canals	Self-funded	Project on hold pending further progress in UK device trials

Table 6.2: Current Marine Energy Projects in New Zealand

6.2.2 Crest Energy Project

Auckland-based Crest Energy originally proposed to deploy the Lunar Energy tidal stream turbine in the Kaipara Harbour in applications for resource consents submitted to Northland Regional Council in July 2006 (Crest Energy, 2006). Crest Energy planned to use 200 units in an extended array. However, new consent applications were submitted in mid-2007 and parts of the original applications were withdrawn. The new applications indicate that Crest Energy is now planning to deploy the OpenHydro ring turbine device (Section 2.3.7) and will move to an incremental development. Although Crest Energy's decision to move to the OpenHydro device may delay deployment of the Lunar Energy device in New Zealand, the latter may eventually be deployed here in other projects.

Northland Regional Council finally held hearings on Crest Energy's consent applications in the week of 26 – 30 May 2008. A decision on the granting of the consents is expected within 3 months. During the week of the hearings, the Minister of Energy announced that Crest Energy would be awarded $1.85 million for the deployment of the first three devices from the Marine Energy Deployment Fund, subject to grant of a resource consent for the project.

6.2.3 Neptune Power Project

The Neptune Power proposal to establish a tidal stream project in Cook Strait garnered a great deal of publicity in 2006 and 2007. In July 2007 Neptune submitted a brief application for consents to establish a single trial turbine at a site near Karori Rip off the south coast of Wellington (and slightly out of the main part of Cook Strait). The site is probably close to the site envisaged for deployment by Tidal Flow Seamills (see Section 6.2.6).

Neptune Power reviewed their plans at a workshop convened by the Electricity Commission, where they unveiled ambitious plans to deploy 900 MW of tidal stream devices off Cape Terawhiti by 2021 (Neptune Power, 2007, see next section).

On April 10 2008 Neptune Power was granted a non-notified consent to install a single prototype device with an export cable connecting to the onshore Vector distribution network (GWRC, 2008). The consent documents indicate that Neptune Power plans to deploy its prototype device in late 2009. The proposed site for the prototype deployment is somewhat east of the site proposed for the utility-scale development.

6.2.4 Power Generation Projects Proposal

This project was first announced in the Business Section of the Sunday Star-Times in mid-2004. The project at that time proposed to establish an array of Pelamis devices on the west coast of the North Island. Power Generation Projects Limited (PGP) sought support from the Heavy Engineering Research Association (HERA) and some of its members accompanied PGP staff to the United Kingdom to meet Ocean Power Delivery in mid-2007. PGP has made no public release on developments since that time. The project was again featured in an article in the Business Section of the Sunday Star-Times (on four projects) in May 2008 but the article did not report any new developments in this project.

6.2.5 WET-NZ R & D Programme

The Wave Energy Technology – New Zealand (WET-NZ) project is a consortium R & D programme funded by the Foundation for Research, Science and Technology. The partners are two Crown Research Institutes, Industrial Research Limited and the National Institute of Water and Atmospheric Research, together with Power Projects Limited, the co-author of this report.

The WET-NZ consortium has developed a point absorber wave device, a quarter-scale version of which was deployed in Pegasus Bay off Christchurch in December 2006. The device has been significantly modified between open ocean deployments during 2007-08 (Figure 6.5). The longest continuous deployment was for 35 days and the device has survived a number of storms. In early 2008 a second version of the device was fabricated to enable parallel testing to continue; the second device has yet to be deployed. However, in May 2008 the original device was withdrawn from Pegasus Bay, refurbished and redeployed at Evans Bay in Wellington Harbour, where it was tested for about 30 days.

Figure 6.5: WET-NZ's Point Absorber Wave Energy Converter

6.2.6 Tidal Flow Seamills Project

This project was first proposed publicly in 2004 but further developments have not been forthcoming. The proposed new vertical axis turbine was to be installed near the Karori Rip, a well-known tidal current off the south coast of Wellington. Power Projects Limited understands that a small-scale version of the device has been fabricated and Tidal Flow Seamills intends to test this device later in 2008.

6.2.7 Natural Systems Limited Project

Natural Systems Limited has acquired the New Zealand and South Pacific licence for the HydroVenturi device. Natural Systems' focus is on small-scale hydro opportunities on rivers and canals, rather than open ocean currents (Natural Systems, 2006). It has a proposed prototype site on a Canterbury canal race.

It appears that the HydroVenturi technology is still at an early stage of development and the company's interest seems to be either in the UK or the US. The New Zealand licence held by Natural Systems Limited will accelerate any deployments here but the delays in device development and the focus on run-of-river or canal applications may mean that it is some time before larger-scale tidal stream applications are realized. For these reasons the HydroVenturi Technology will not be considered further.

6.2.8 Domestic Marine Energy Project Timetables

There are a number of marine energy project developers now active in New Zealand. It is instructive to review the proposed development timeframes for the more advanced of these projects.

Neptune Power has secured consents and is planning its first prototype deployment by the end of 2009 (Section 6.2.3). The development of its commercial tidal stream turbine project will then follow an incremental development schedule (Table 6.3, after Neptune Power, 2007).

Date	Proposed Activity	Units Installed	Capacity (MW)
2008	Consents granted for single prototype deployment	-	-
2009 – 2011	Single twin-turbine prototype	1	1
2011 – 2012	First commercial stage	30	150
2013 – 2016	Second commercial stage	60	300
2017 – 2021	Third commercial stage	90	450
TOTAL		**180**	**900**

Table 6.3: Proposed Development of Neptune Power Project

Neptune's proposal is extremely ambitious. It has taken the New Zealand wind industry 14 years to move from one 225 kW turbine to 320 MW of wind capacity, utilizing a mature and proven wind turbine technology. Neptune Power's proposal is to install greater total capacity, utilizing a new, as yet untested technology, in very difficult marine conditions. It will be a very considerable challenge to deliver this project to the timetable proposed by the developer.

Crest Energy has sought consents for its tidal stream project in the Kaipara Harbour (Section 6.2.2). Its project plan has four incremental stages with progressive increases in numbers of turbines. Note that the timetable shown takes the mid-point of the forecast periods for each stage (Table 6.4, after Crest Energy, 2008). This timetable is much more reasonable but is still a considerable stretch, given that Crest Energy have yet to secure their consents for the first stage of development. Undoubtedly, the MEDF grant they recently received will provide a stimulus to their activities.

Date	Proposed Activity	Units Installed	Capacity (MW)
2008	Consents applied for; Granted and not appealed?	-	-
2010	First commercial stage	20	20
2013	Second commercial stage	20	20
2016	Third commercial stage	40	40
2022	Fourth commercial stage	120	120
TOTAL		**200**	**200**

Table 6.4: Proposed Development of Crest Energy Project

6.3 FORECAST GROWTH OF MARINE ENERGY IN NEW ZEALAND

6.3.1 Marine Energy Projects and Deployments in New Zealand

There are some common features to the forecasts for deployment of marine energy, the timetables put forward by marine energy project developers and the historical development of wind energy, with which the development of marine energy may have some corollaries.

1. Assessments made in the early 2000s have proven unduly optimistic. Active device developments were advancing rapidly at that time but subsequent progress slowed due to equipment problems, fabrication lead times and deployment delays. None of the forecasts cited above accurately predicted the present state of deployments
2. All the forecasts show slow early progress but an accelerating pace of development post-2010. This acceleration – reflected as exponential growth curves – matches the actual development of wind capacity quite well. As a result the 2005 and 2006 forecasts become increasingly over-optimistic post-2010.

Whilst the forecast numbers may have proven over-optimistic, the forecast trends may still be correct. Early forecasts may have predicted a '*false dawn*' on the basis of contemporaneous optimism. The start has been delayed, perhaps, but there is no reason to think that marine energy could not eventually grow at the 25 - 35% annual growth rates that the wind energy industry has experienced. The reasons why this exponential growth may eventually occur are as follows:

1. A trend for device/project developers over the last two years to secure multiple international project locations
2. Most projects are proposed as multi-unit project deployments
3. The size of proposed multi-unit arrays has increased
4. National testing/deployment centres is increasing, simplifying and accelerating the time to deployment for devices under development.

The supportive actions in the New Zealand Energy Strategy (MED, 2007) will accelerate activity here. Nonetheless, the optimism of international forecasts, made over only 3 – 4 years ago, justifies a more measured forecast for the uptake of marine energy in New Zealand. Potentially accessible marine energy resources in New Zealand are large but the cost and difficulties of accessing and harnessing those resources are very significant, particularly whilst marine technologies remain immature and the supply chain has yet to develop.

6.3.2 Forecasts for Total Marine Energy Capacity

There have been a number of early-stage forecasts of the potential total capacity for marine energy in New Zealand. Perhaps the most extensive study to date has been done by Sinclair Knight Merz in a series of Regional Renewable Energy Assessments (SKM, 2006 – 2008). The reports document the renewable energy potential of regional council areas. The series is still incomplete because East Coast, Wairarapa and Southland studies have not been published. However, the eleven reports that have been produced have a cumulative total of over 6,000+ MW of wave energy potential and low hundreds of MW of tidal energy. It would be reasonable to assume that the total wave capacity would be less than 10,000 MW, since neither the East Coast, nor Wairarapa will add significantly to the total. Contrary to the results of the present study, SKM identify *c.* 1,000 MW of wave power on the Wellington coast.

SKM's total figure is significantly lower than Carnegie Corporation's 30,000 MW forecast for wave potential (Carnegie Corporation, 2008). The latter may be a provisional estimate based on very coarse grid mapping and is probably less reliable than the SKM estimate. SKM's forecasts for tidal/ocean current potential are much lower – in the low 100s of MW. SKM recognizes little tidal/ocean current potential in the Wellington region, which is contrary to the results of this study and certainly contrary to Neptune Power's previous suggestion that there is 12,000 – 13,000 MW of tidal energy potential in the north-central and eastern part of Cook Strait.

In Power Projects' view it is premature to attempt a total forecast for the capacity of marine energy in New Zealand. The large range of estimates made by others (<10,000 to 30,000 MW for wave) serves to demonstrate the difficulty of doing such an assessment. In any event these are estimates of the potential resource and the likely recoverable reserves, *i.e.,* the total capacity of the economic projects, are likely to be considerably lower than these very large figures.

Whilst these very large estimates may also serve to promote marine energy, they set an unrealistic expectation of the likely size and timing of the contribution of marine energy, which may ultimately discredit the nascent industry. A more measured approach is justified: identifying regional wave and tidal/ocean potential, by integrating resource data and device performance data to derive potential project capacity (in MWs) and annual generation capacity (in GWh/year). In due course project developers will do more detailed analysis matching device performance and resource assessments on a site-by-site basis.

6.3.3 Forecasts for Uptake of Marine Energy in New Zealand

A number of New Zealand-based organizations have commented on the development of marine energy technologies, suggesting that they lag behind wind technologies. In 2006 the New Zealand Business Council for Sustainable Development cited dates of '*demonstration use'* by 2025 and '*early commercial use'* by 2050 (NZBCSD, 2006). Both sets of estimates are unjustifiably pessimistic and, recent deployments have pre-empted these dates.

Meridian Energy cites a more optimistic figure of 10 - 25 years (Meridian Energy, 2008) and an overseas investor in marine energy technologies overseas, the Triodos Bank, has suggested that technologies are only 5 years behind wind devices (Triodos Bank, 2008). An estimate of 5 – 10 years is probably appropriate with New Zealand gradually catching up with the leading countries (Scotland, Portugal, United States and Canada), as domestic interest and investment grow.

With respect to contribution of marine energy to New Zealand's energy supply portfolio, the only published estimate was published in the "*Energy Outlook to 2030*" (MED, 2006). In the '*Renewables Scenario*' 200 MW of wave energy capacity was due to be installed by 2030. This figure seems conservative by comparison with the plans of the two current project developers.

Power Projects Limited believes that there will be at least three demonstration projects in the water within the next 3 – 5 years and the first commercial deployment can be expected within 3 - 7 years. Whilst the present slow pace of developments here may continue for 3 – 5 years, there is likely to be exponential growth, once domestic and international device prototypes mature into commercial products. The pace of development lies partly in the hands of developers, working to reduce unit costs of marine-generated electricity. However, the macro-economic environment (ongoing high energy prices, concern about global warming, carbon pricing and emissions trading) are likely to have a bigger impact in accelerating the development and uptake of marine energy technologies overseas and here in New Zealand.

PART 7: GREATER WELLINGTON REGION CASE STUDY

7.1 INTRODUCTION

Previous sections have covered the development of marine energy technologies and presented the national and regional wave, tidal and ocean current energy resource evaluation and mapping. Detailed studies of wave resources in six nationally distributed areas and tidal/ocean current resources in the Southland Coastal Marine Area (CMA) have been presented. In this final part of the report, a case study for the Wellington region CMA is presented, covering mapping of the wave, tidal and ocean current resources, combined with a review of constraints on activities in the CMA, with particular respect to marine energy and local coastal uses and occupation.

7.2 WAVE ENERGY RESOURCES

It was originally intended that the wave resources of the Wellington CMA would be evaluated. The proposed area was the same area as that chosen for the tidal/ocean current study (Figure 5.8). However, early results indicated that the wave resources in this area were very limited and further work was discontinued. As an alternative a site on the lower Wairarapa coast was studied in detail instead and the results of the analysis of this site are presented in Section 5.2.

7.3 TIDAL & OCEAN CURRENT ENERGY RESOURCES

The tidal & ocean current resources of Cook Strait have been widely recognized. Although there are significant tidal/ocean current energy resources (over 13,000 MW by some authors) attributed to the region, there has been little attempt to quantify the recoverable reserves of energy that could be extracted from the tidal and ocean currents passing through Cook Strait.

The Cook Strait is only 24 kilometres wide at its narrowest part, where it is aligned approximately north - south (Figure 7.1). In this central region of the Strait, the Terawhiti Sill is the shallowest part of the divide between the North and South Islands, with the water depths only to around 240 m. To the north of the Sill, the Narrows Basin is a broad channel that extends to 350 m deep, while to the south the bathymetry is typically shallower (~140m), truncated by the cook Strait Canyon (which is a westerly extension of the Hikurangi Trench. The complex bathymetry has significant effects on the tidal flows through the Strait (Figure 7.1).

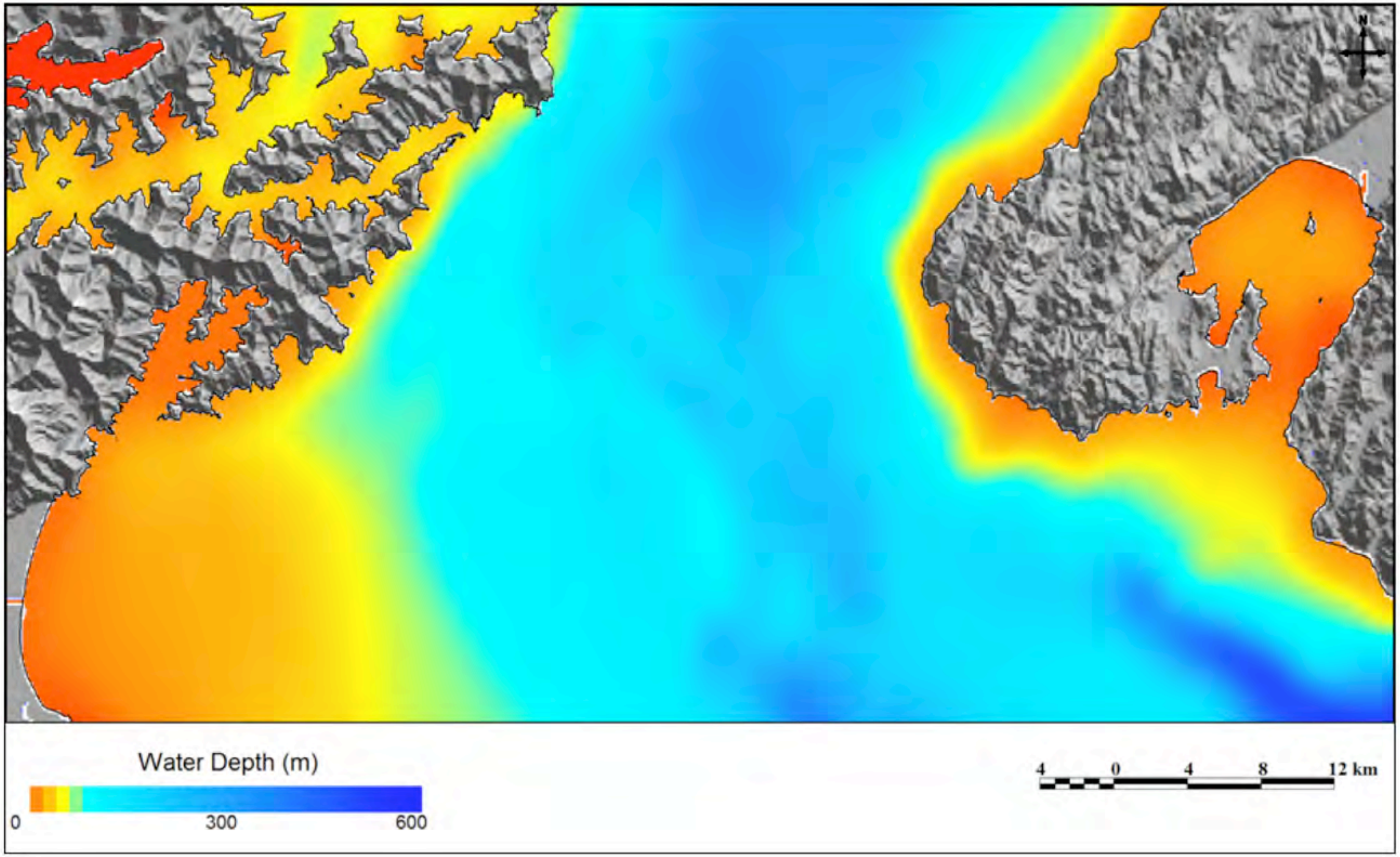


Figure 7.1: Bathymetry of Cook Strait

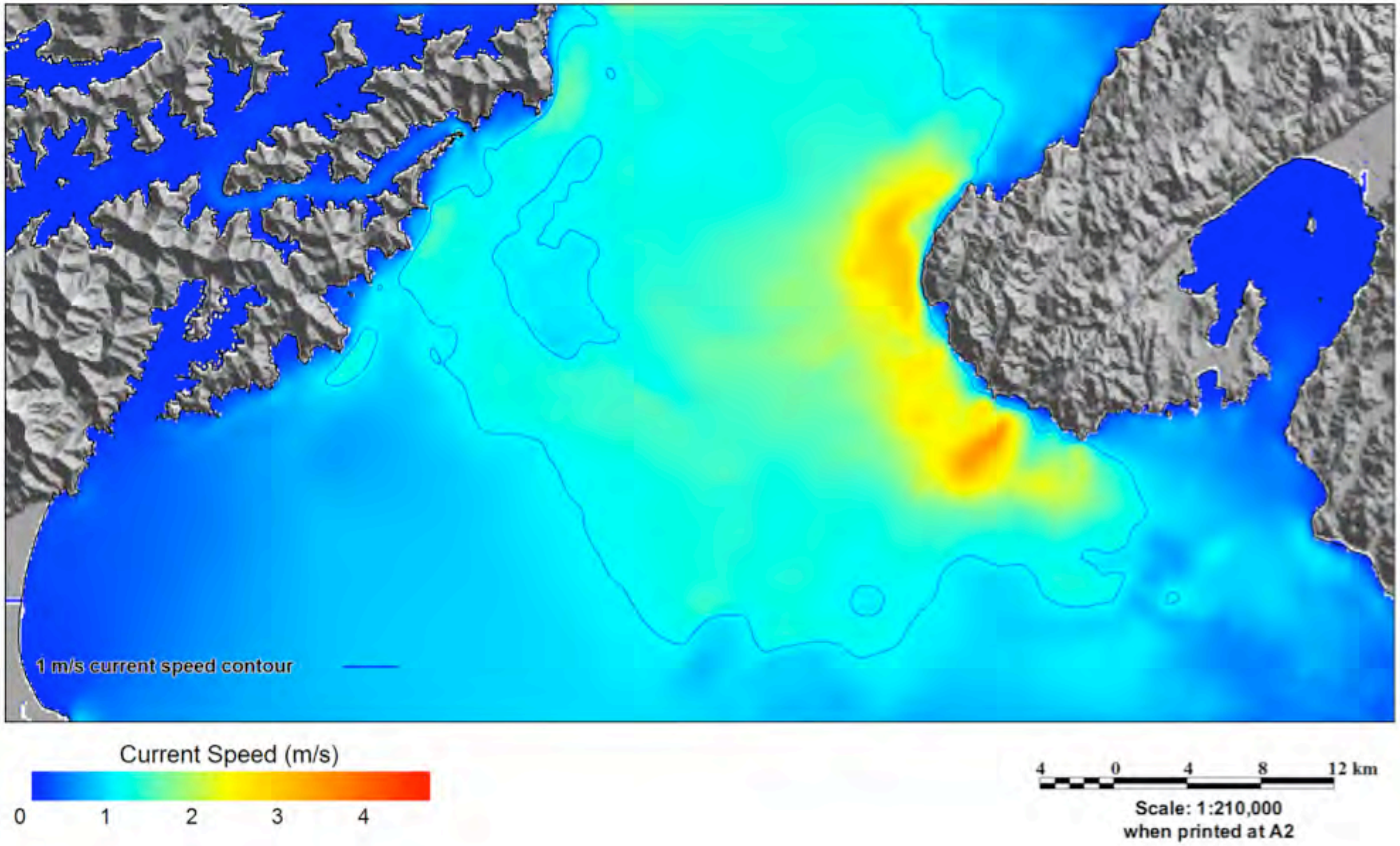


Figure 7.2: Depth-averaged Mean Spring Tidal Currents in Cook Strait

One of the main reasons for strong tidal flows through Cook Strait is the phase difference of the principal lunar semidiurnal constituent (M2). Essentially, the high tide level on the Eastern side precedes the high tide on western side of the Strait by around 5 hours. It is this difference in timing that leads to the high flows in the Strait, not the water levels. Indeed, the tidal range in the Cook Strait is relatively modest (~1 m) compared with most locations in New Zealand. Localized effects within the Strait mean that the strongest tidal currents are adjacent to the Wellington Southern coast, where there are clear zones of flow acceleration exceeding 1 m/sec.

Further, the effect of local bathymetry can clearly be seen in the acceleration of the currents immediately west and south of the peninsula. There are at least four areas (at least 2 km^2 each), where currents may exceed 2.5 m/sec. However, local turbulence will be a significant factor for tidal project developers in these zones of high flow.

More details on the modelling and characterization of the tidal current resources in Cook Strait can be found in Appendix C.

The results of the analysis of five sites in Cook Strait are presented in Section 5.4.2 to enable a comparison with the modelled site in Foveaux Strait.

7.4 CONSTRAINTS ON MARINE ENERGY PROJECTS

Many constraints may affect development of marine energy projects within the Coastal Marine Area (CMA). These include regulatory requirements to obtain resource consents, to meet environmental requirements (including monitoring), to consult with affected and interested parties and to work with others undertaking competing activities within the same space.

Regional and local authorities may have different requirements on project developers, depending upon their operative plans (see below) and there may be specific issues and requirements, with which any project developer will have to comply. The following sub-sections relate to potential projects within the Coastal Marine Area (CMA) administered by Greater Wellington Regional Council (GWRC). A prospective marine energy project developer would do well to make early contact with the relevant regional council responsible for the CMA, within which the developer has identified a potential project site, to establish the specific requirements.

No resource allocation regime for marine energy projects is in place in New Zealand, the only requirement for device/project developers being that they must secure consents under the Resource Management Act 1991 (RMA), for space occupation, erection of structures, taking of energy and, possibly, discharges. The RMA process is essentially an environmental management regime, operating on a '*first come, first served*' basis. The authorities, which grant consents under the RMA, cannot consider the trade competition aspects of the proposals, nor can they consider the financial and technical capabilities of project developers, unless there are related potential environmental implications. The principal focus of the RMA is on sustainable management of natural and physical resources, and "environment" has a very broad definition under the RMA.

Before reviewing the actual constraints on marine energy projects, it is appropriate to review the policies and regulations, operative in the Wellington CMA.

7.4.1 Operative Policies and Regulations

A hierarchy of legislative and regulatory policies controls activities in the CMA. As noted above the primary legislative instrument affecting marine energy projects is the **Resource Management Act 1991** (RMA) and later amendments. The next layers in the hierarchy are the **New Zealand Coastal Policy Statement** (NZCPS) prepared by the Minister of Conservation, **Regional Policy Statement** (RPS) and the **Regional Coastal Plan** (RCP), both prepared by the regional council. Each document has to '*give effect to*' the documents higher up in the hierarchy. The Act gives councils functions, under section 30 of the RMA, for managing the CMA, with the Minister of Conservation having a role. More recently, an amendment to section 7 of the RMA requires consenting authorities to '*give particular regard to*' the benefits to be derived from the use and development of renewable energy. The current Labour-led Coalition government is in the final stages of introducing a **National Policy Statement on Renewable Electricity Generation**, which will be notified possibly in July 2008 and in place by early 2009. This is intended to give councils and the Environment Court specific guidance on how to deal with nationally significant renewable energy projects.

The **New Zealand Coastal Policy Statement 1994** (NZCPS), currently under statutory review, established a requirement that particular scheduled activities which have significant or irreversible adverse effects on the CMA are '*restricted coastal activities'*, *i.e.,* discretionary or non-complying activities and decided upon by the Minister of Conservation. The erection of structures, which provide a significant barrier to water movement, subject to specific limits, *e.g.,* a marine energy converter, could be a restricted coastal activity. The laying of submarine cables is not a restricted coastal activity. The **Proposed New Zealand Coastal Policy Statement 2008** was notified on 8 March 2008 and submissions closed on 7 May 2008. A Board of Inquiry will hold public hearings in June – July 2008.

Below the NZCPS is the **Wellington Regional Policy Statement** (RPS), which aims to maintain the quality of the Wellington region's coastal environment. The objectives and policies are intended to provide an overview of the resource management issues of the region and policies and methods to achieve integrated management of the natural and physical resources of the whole region. The RPS gives effect to the intentions of the NZCPS with respect to activities in the CMA but the RPS also has positive intentions with respect to marine energy. Noting the current high level of dependency of the regional economy and communities on non-renewable sources of energy and the '*growing number of adverse effects*' that result from the production and use of that energy, the RPS recognizes marine energy and seeks efficient use of renewably generated energy, including marine energy.

A **Draft Regional Policy Statement for the Wellington region 2008** was issued by GWRC in early 2008. As required by section 59 of the RMA, the RPS aims to make 'sustainable management' the core for management of the natural and physical resources of the region. This new draft statement specifically acknowledges the rich renewable energy resources of the Wellington region and will provide direction on the importance of renewable energy projects, albeit overlaid with considerations on a case-by-case basis.

The **Wellington Regional Coastal Plan** (RCP) is the plan that gives effect to the intentions and provisions of the RMA, NZCPS and RPS in the Wellington CMA, seaward of Mean High Water Spring tides (MHWS). The present plan promotes economic and social well being (arising from economic activity, such as electricity generation), the development and use of appropriate structures in the CMA (*e.g.,* would apply to a (marine) energy converter) and ensures that factors, such as the effects of waves and tides, sea level rise and coastal hazards on any man-made structure, are taken into account. There are also policies, whose intent is to address activities, whose adverse effects are short term, minor or reversible.

This hierarchy of legislative and regulatory instruments provides the basis on which regional councils (and district councils for shore-based activities) can consider and evaluate proposed developments, such as marine energy projects. Any developer would be well advised to understand the constraints imposed by these instruments not only on any proposed project. The recent award of a non-notified resource consent to Neptune Power provides a useful case study of the outcome of a marine energy project consent application.

7.4.2 Neptune Power Consent Area and Export Cable Route

Any marine energy device/project developer must secure consents from regional and local councils under the RMA 1991, prior to undertaking any physical works. On 10 April 2008, GWRC granted the first (non-notified) consent for a domestic marine energy project to Neptune Power. The consent has been granted for 10 years in an area south of Red Rocks off the south coast of Wellington (Figure 7.3; page 72).

Neptune Power has consents to undertake three activities:

1. Place, use and maintain a prototype tidal stream generation turbine and associated export cables,
2. To disturb the foreshore and seabed, and
3. To occupy the coastal marine area (CMA).

The consent also enables the developer to harness the energy.

Any device developer would need to seek such consents from the regional authority responsible for the CMA (from high water out to 12 nm from the coast) where their chosen site lies. There are likely to be further consent requirements for export cables crossing the beach and for any onshore structures, *e.g.,* a substation or monitoring facility but these are sought from the local district or city council, Wellington City Council in Neptune Power's case. If the cable crosses a marginal strip administered by DoC, a concession under the Conservation Act may be required.

These activities are '*discretionary*' in the Wellington CMA, meaning that the activities are not permitted as of right and the regional council applies its discretion in granting a coastal permit for the activity. In Neptune Power's case, the GWRC granted a '*non-notified*' consent, meaning that public submissions and hearings were not required. Neptune Power had been required to consult with a number of '*affected parties*', and to obtain their written approval under section 94 of the RMA, prior to GWRC deciding whether or not to publicly notify the application.

Because marine energy deployments are new activities in New Zealand, there is little information available on their environmental effects. GWRC took the approach that empirical acquisition of such information, by permitting the deployment of a single prototype turbine with substantial monitoring equipment, was required. Experience gained with the prototype turbine will contribute to further consent applications for a larger-scale multi-unit array, which is what Neptune Power is ultimately proposing (Neptune Power, 2007).

The consent was granted with immediate effect for 10 years, although the device will be deployed for only between 3 and 5 years. First deployment is quoted as late 2009. The location of the prototype device and the 11 kV export cable route (6 – 8 km) have been approved. The export cable will be armoured and buried by a subsea cable plough.

Neptune Power had to consult with a number of affected and interested parties as part of their application. The identification of and consultation with affected parties is good practice for any developer seeking a non-notified consent. Affected parties will be different depending on the choice of site. Neptune Power consulted with the following:

1. *Tangata Whenua* (Wellington Tenths Trust and Ngati Toa Rangatira Inc.)
2. The Department of Conservation (DoC)
3. Wellington Harbourmaster
4. Cook Strait Commercial Fishing Association
5. CRA 4 Rock Lobster Industry Association Incorporated

None of these parties raised objections to the Neptune Power proposal.

Other interested parties, which were consulted by GWRC and/or Neptune Power included:

- Ministry of Economic Development
- Energy Efficiency and Conservation Authority
- Maritime New Zealand
- Ngati Rarua Iwi
- Transpower New Zealand (see next section)

Each party offered its views but the only consent condition arising was a requirement for Neptune Power to provide the actual co-ordinates for their device and export cable to Land Information New Zealand (LINZ) on deployment.

The resource consent granted to Neptune Power goes on to deal with a number of environmental issues that arise from the placement and operation of the prototype tidal stream turbine, effects on pelagic and benthic sea life and the seabed, the effects of accidental movement and ongoing maintenance (including intermittent removal) of the device. As the first deployment project there is a substantial requirement for monitoring of effects, including marine life (cetacean and marine mammal) collisions, fish strikes, acoustic effects and electromagnetic fields.

The consent is conditional on Neptune Power and its contractors meeting a range of specific conditions, relating to the:

- Provision of an Operations and Maintenance Plan
- Turbine and Mooring Structure
- Operational, Maintenance and Monitoring
- Monitoring and Reporting
- Unintended Detachment
- GWRC Review

The requirements on Neptune Power are extensive but no more onerous than for other marine activities. Future device/project developers should be able to benefit from Neptune Power's experiences, assuming that they remain on track to be the first project to deploy a tidal stream turbine in the CMA. Resource consent applications are very good, but general, guides to the issues that marine energy project developers will face in securing consents at their own chosen locations, *e.g.,* Neptune Power, 2007 & 2008; Crest Energy, 2006 & 2007; Willis and Handley, 2008.

It is important to note that the consents do not provide an exclusion zone on other activities. Vessels can navigate over the top of the area that the turbine will be located in and over the export cable route but there is clearly an issue for any vessel, using trawling or dredging equipment.

7.4.3 Cook Strait Submarine Cable Protection Zone

The first national grid power cables were laid across Cook Strait in 1964 and the Submarine Cables and Pipelines Protection Act 1966 was passed to protect them. There were subsequently a number of instances of cables being displaced, damaged or even broken, probably as the result of trawling or small boat anchoring. The cost of repair/replacement runs into millions of dollars, particularly as cable-laying vessels are not readily available in New Zealand. In 2006 Transpower estimated that replacement of a cable would cost more than $80 million, whilst repairing a power cable would exceed $30 million (Transpower and Ministry of Transport, 2006). The consequential effects of loss of transmission of both electricity and communications would be severe and, potentially, even more expensive.

As a result of instances of damage to the cables, a general increase in fishing activity and evidence of illegal fishing, the Act was amended in 1996 to increase substantially the penalties for damaging the cables or carrying out illegal activities and a Submarine Cable Protection Zone (CPZ) was created to protect the cables. Presently the Cable Protection Zone is about 7 km wide but narrows sharply at each end, where the submarine cables come ashore – at Fighting Bay in Marlborough and Oteranga Bay on the Wellington coast (Figure 7.3).

The CPZ protects both Transpower's high-voltage direct current (HVDC) power cables and fibre optic communications cables owned by other companies. Although both sets of cables have protective armoured coatings and are designed to withstand normal seabed and tidal conditions, they are still vulnerable to damage. In some cases the cables are suspended above the seafloor due to seabed irregularities.

All fishing/anchoring within the CPZ is prohibited with the exception of limited daylight fishing (crayfish, paua, kina and set nets) within 200 m of the low water mark and outside the marked landfalls at Fighting Bay and Oteranga Bay. Support boats must not anchor or indirectly attach themselves to the seabed within the CPZ.

Transpower and the Ministry of Transport jointly manage the CPZ. Activity within the CPZ is monitored by sea and helicopter surveys and Protection Officers have powers to order vessels to leave the CPZ and to seize fishing equipment left there (*e.g.,* nets and cray pots). Vessels with partly deployed nets are considered to be fishing and vessels, which accidentally drift into the CPZ, are still liable.

If a vessel is found to have partially deployed fishing or anchoring equipment over the side, then the onus is on the vessel operator to prove that the vessel was not fishing or anchoring – the reverse of the normal onus of proof under law. Penalties for breaching the Act include $100,000 for fishing or anchoring, $250,000 for damaging a cable and forfeiture of the vessel and other property.

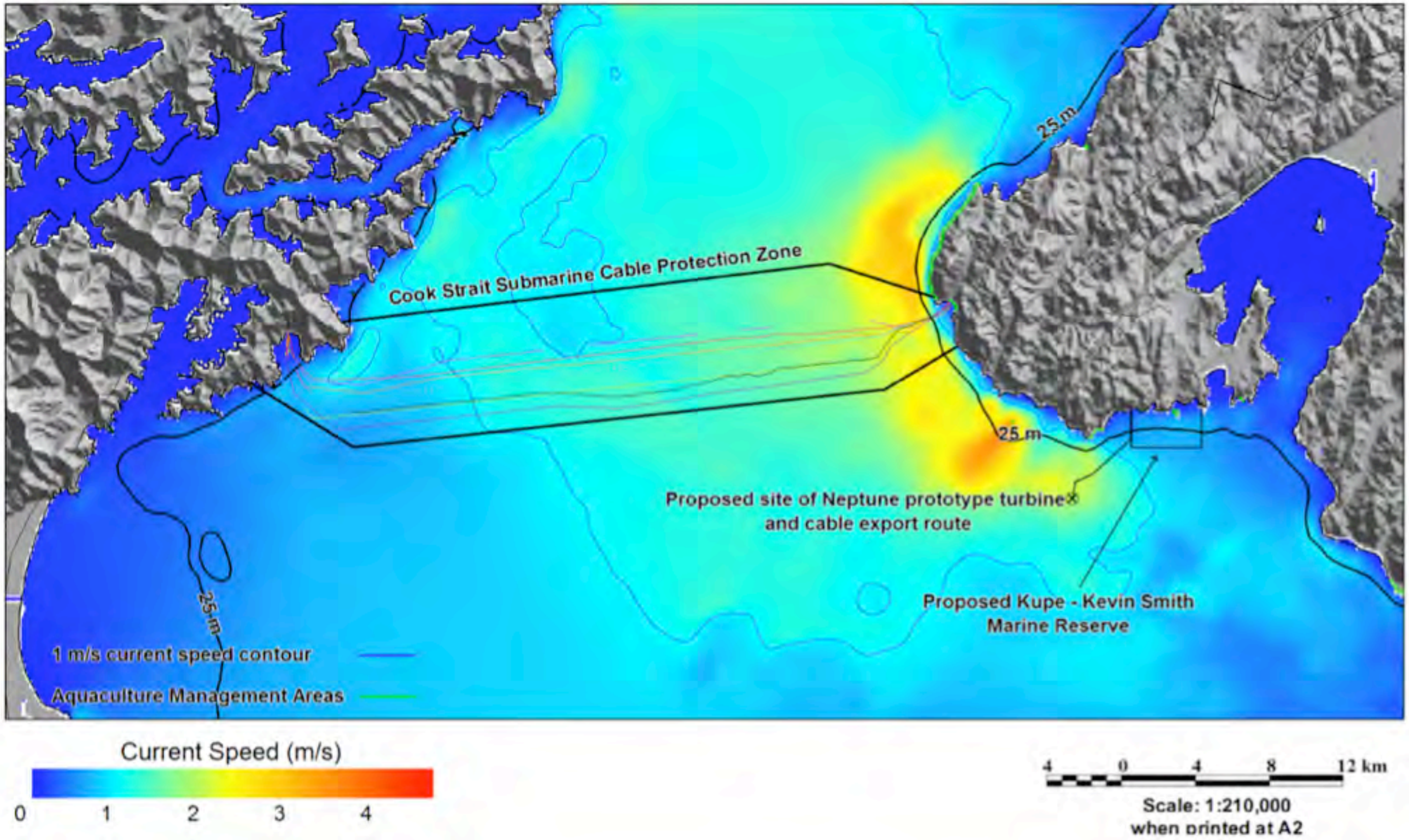


Figure 7.3: Maritime Constraints in the Cook Strait CMA

Note: discontinuities in the submarine cables indicate where the cables are buried

7.4.4 Marine Reserves

Marine reserves are specified areas of the sea and foreshore that are managed by the Department of Conservation to preserve them in their natural state as the habitat of marine life for scientific study. Within a marine reserve, all marine life is protected: fishing and the removal or disturbance of any living or non-living marine resource is prohibited (except for permitted monitoring or research).

Marine reserves became possible under the Marine Reserves Act of 1971 (MRA), largely in response to pressure from New Zealand's scientific community – hence the scientific bias in their establishment. Although reserves may now be established with consideration for recreational and traditional use, the scientific emphasis remains. However, there is a new Marine Reserves Bill before Parliament, which could change the purpose from primarily scientific. Although anybody may propose a marine reserve, it is an onerous process. In practice therefore, they are usually proposed by the Minister of Conservation, universities, any body administering land, which has a frontage on the sea or any body engaged in scientific study of marine life or natural history. There are currently over thirty marine reserves, since the first was established in 1975. However, the cumulative area of marine reserves around the mainland territorial sea is small, amounting to less than the area of the smallest National Park (Abel Tasman).

The principal permitted activities within a marine reserve are public observation of marine life, navigation and anchoring. Fishing is not allowed, nor are discharges into a marine reserve. Exploration and extraction of minerals, harbour works and any marine energy project are also prohibited, unless they were explicitly allowed in the original Order-in-Council, establishing the reserve. Within the Wellington CMA there is one principal marine reserve – the Kapiti Island Reserve - and one proposed reserve, the Wellington South Coast Marine Reserve.

<u>Kapiti Marine Reserve</u>

The Kapiti Marine Reserve links the Kapiti Island Nature Reserve and the Waikanae Estuary Scientific Reserve on the adjacent mainland. The reserve extends either side of Kapiti Island and all marine life, habitats, objects and structures within the reserve are protected (Figure 7.4). The reserve was established in 1992.

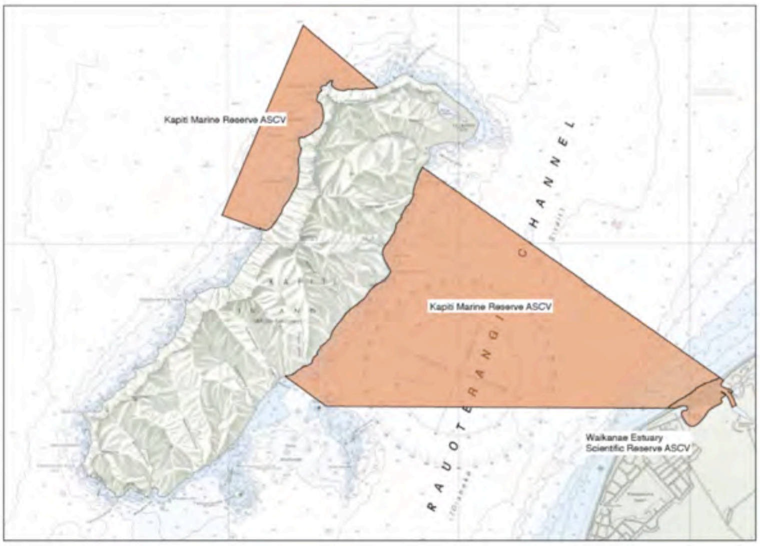


Figure 7.4: Kapiti Marine Reserve (source: GWRC)

Wellington South Coast Marine Reserve

The Ministers of Conservation, Fisheries and Transport have approved the application for the Wellington South Coast reserve (sometimes referred to as the "Kupe/Kevin Smith Marine Reserve", although the name has not been formally adopted). The reserve has been surveyed but it has yet to be gazetted and created by an Order-in-Council. Over the years the proposal has progressed through DoC, Ministry of Fisheries and Ministry of Transport department reviews and the presently proposed reserve, which covers 840 hectares, includes all foreshore up to the Figure 7.5). This is slightly smaller than the 969 hectares originally proposed.

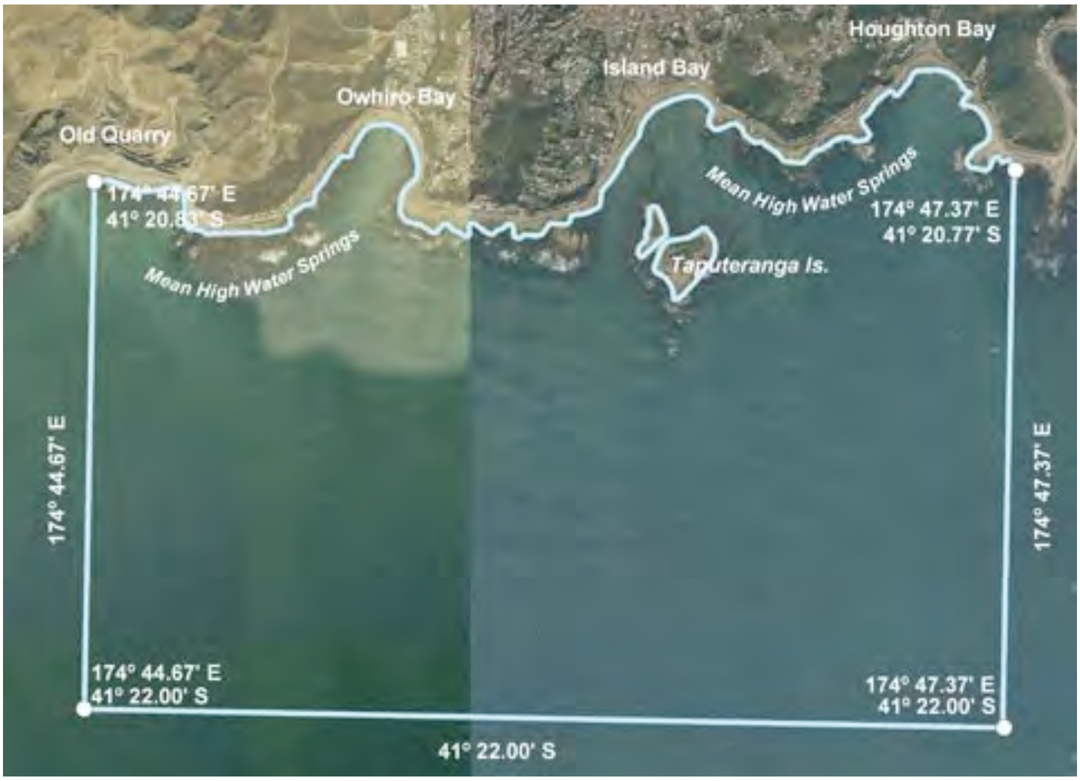


Figure 7.5: Final Area of Wellington South Coast Marine Reserve

Although the reserve has not yet been gazetted, it would now be extremely unlikely that any marine energy project would be allowed to proceed within the proposed area of the reserve before its gazettal and it will be forbidden once the reserve is formally declared. Note that Neptune Power's export cable route runs along the western boundary of the proposed reserve before coming ashore at the old quarry.

7.4.5 Areas of Significant Conservation Value

The Regional Coastal Plan defines Areas of Significant Conservation Value (ASCVs), within with most activities are classified non-complying. Outside these areas, activities such as marine energy deployments may be undertaken subject to obtaining a consent from the regional council. The current and proposed marine reserves were covered in the previous section but there are other ASCVs. With the exception of the Bridge ASCV, which extends between Mana Island and the mainland coast, the remainder of the ASCVs are limited to estuaries, narrow strips of foreshore or reefs in separate and discrete locations around the coast (Figure 7.3; page 72). As such they are unlikely to be interesting to or problematic for marine energy project developers, except potentially as crossing points for submarine export cables.

7.4.6 Environmental Issues

A number of environmental issues will impact on future marine energy projects in the Wellington CMA. These include, but are not limited to, the following:

1. **Extreme weather conditions –** Cook Strait and the south coast of Wellington experience significant periods of extreme weather during winter months. Maximum significant wave heights have exceeded 10 m in the period 1998 to 2007, although periods of extreme waves do not persist for long (see Appendix 3, table 6.16). Such waves are problematic for surface-piercing or floating devices in terms of survival, general wear and tear and access for repairs and maintenance. Submarine current conditions are likely to be less variable and extreme. Nonetheless, all devices will need to be designed to survive these conditions, whilst operating efficiently in a range of normal conditions. Project developers will need contingency plans to address issues such as anchors dragging and unintentional movement of devices, particularly in light of the location of the HVDC cables entering Cook Strait at Oteranga Bay. Lifting and movement of subsea cables will also be potentially problematic.

2. **Marine mammals and whale migration** – whales, seals and dolphins occupy or migrate through the Wellington CMA. Common and dusky dolphins are frequently observed in large numbers in the CMA and occasionally in Wellington Harbour (DoC, 2008). Humpback, Bryde's and blue whales have all been sighted in Cook Strait and rarely in Wellington Harbour (McComb, P., *pers. comm.*, 2008). New Zealand fur seals are known to have breeding sites in Cook Strait.

   Whales migrate northwards along the east coast of New Zealand at all times of the year, with some individuals passing through Cook Strait and northwards up the west coast of the North Island. There has been a steady increase in recorded numbers since 2000, possibly as the result of the closure of the Perano Whaling Station in Tory Channel in 1964. Over 50 humpback whales were recorded passing through Cook Strait in the winter of 2000 (Gibbs and Childerhouse, 2001). An annual two-week survey has been conducted in successive seasons with 40 – 45 humpback whales recorded during these surveys.

   The Department of Conservation and Te Papa made whale and other marine mammal sighting and stranding databases available but mapping of migration routes would be valuable in assessing locations. Such data is not available, so site-specific analysis is not possible (Bott, N., *pers. comm.,* 2008). Until such data is available, the whole of Cook Strait can be regarded as a migration route for whales.

   The effect of marine energy technologies on migrating whales is difficult to assess and monitoring of deployments, such as the proposed Neptune Power prototype, will provide the best evidence.

   Other marine life – fish and other pelagic species are unlikely to be affected by submarine, surface-piercing or floating devices. Fish tend to congregate around marine structures and 'fish strike' is very rare. Whilst concern has been expressed about the effects of rotating blades on submarine tidal turbines, there is scant evidence from deployments of any detrimental effects to fish life, principally because the speed of rotation of submarine turbines will be relatively slow (~20 revolutions per minute). Fish and other pelagic marine life should be able to pass through the rotor without damage. Device developers are mitigating any impacts by either shrouding the turbine blades or alternatively utilizing open-ring turbines (see Sections 2.3.6 and 2.3.7).

Whilst the East River of New York may not be the best analogue for the Wellington CMA, Verdant Power has conducted an extensive monitoring programme there, including a continuous, almost 3-dimensional sonar survey (Corren, D., *pers. comm.*, 2008). During the course of this survey, fish and diving birds have been found to avoid the six in-stream tidal current turbines and no collisions were observed. Further, as might be logically expected, fish and other marine life tends to avoid the higher current velocity flow regions, where the turbines are located, preferring the lower velocity flow regions, thus naturally avoiding the turbines.

3. **Energy extraction** – removal of energy by device arrays will cause downstream changes, though these may be negligible. Wave height reductions may be up to 10 – 15% behind wave arrays but wave height is restored by diffraction within 3 – 4 km downstream of the array (EPRI, 2004). Energy extraction by submarine tidal/ocean current turbines is likely to be less serious, although the effects of turbulence may be greater. Since Cook Strait currents are reportedly turbulent naturally, any increase in turbulence may be minimal. Further research is required on this topic.
4. **Sediment deposition and movement** – energy extraction caused by the presence of devices or by their energy extraction is likely to cause some increase in sediment deposition and may affect natural movement patterns. Again these effects may be minimal and monitoring, which will be required as a resource consent condition, should provide evidence of any effects.

There will also be considerable environmental benefits from the deployment of marine energy projects in the region:

1. **Absence of visual and noise effects** – marine energy devices, particularly submarine tidal current turbines will have no visual or noise impacts on humans. Effects on marine life are also likely to be negligible. Even surface-piercing devices, such as wave point absorber or attenuator devices are unlikely to be visible, if located sufficiently far offshore. Although seawater in the region is not particularly turbid, except during storms, most marine life does not navigate visually. Tidal/ocean current turbines are unlikely to generate significant audible noise. Neptune Power's consent indicates that its prototype will generate less noise than the Cook Strait ferries and in high current conditions, predicted noise levels from the turbine will be less than ambient levels. Indeed, it may be necessary to install '*pingers*' to warn and discourage curious marine mammals from venturing too close.
2. **Offsetting thermal generation** – if and when marine energy technologies become commercially competitive, developers may favour them, seeking to minimize or reduce their carbon footprints. The introduction of the proposed emissions trading scheme and the Government's stated 'preference' for renewable generation will favour marine energy developments, over fossil fuel generation.

7.4.7 Fishing

Commercial, customary and recreational fishing are important activities in the Wellington region. Fishing activities range from recreational and customary collection of paua, rock lobster and kina close to the foreshore to deeper-water commercial fishing (*i.e.,* less than 100 m, for hoki and other species) further out in the CMA. The MRA, Fisheries Act and Submarine Cables and Pipelines Protection Act exclude fishing activities from the CPZ, marine reserves and ASCVs.

General information on exclusion zones and fishing management areas for specific species can be found on the Ministry of Fisheries' NABIS on-line map database (www.nabis.govt.nz). Further details on species-specific fishing exclusion zones can be found in reports by the Department of Conservation (Froude, 2004), although the Ministry of Fisheries administers the exclusion zones.

Fishing interests are likely to have concerns regarding both spatial exclusions around marine energy projects and potential effects on fish stocks. It is likely that marine energy projects will require navigation and fishing exclusion zones around them. This exclusion may have an impact not only on fishing but on fishers' access to more distant grounds. There is also a perception that marine energy projects will add to the cumulative impact of closures for other reasons (marine reserves, AICVs). Fishers already face these exclusions as well as specific issues, such as Fisheries Act regulations and a ban on vessels >45 m in length within 1 nm of the coast.

The New Zealand Seafood Industry Council (SeaFIC) advises that fishing activities are likely in all areas of the CMA that are not subject to exclusions. The absence of any indication of active fishing does not mean that areas where marine energy projects may be proposed will not compete for space for fishing or navigation of fishing vessels. Early direct contact with quota owners and other fishers will determine definitively the location of areas that are most important for fishing in any part of the CMA (or alternatively, less important). SeaFIC can direct marine energy project developers to the appropriate quota owners and other fishers.

7.4.8 Navigation

Cook Strait and the south coast of Wellington are sea areas with constant coastal shipping. Commercial and fishing vessels pass through Cook Strait and there is almost hourly passages of the Cook Strait ferries between Wellington and the entrance to Tory Channel. There are fewer vessel movements east of Wellington Harbour, around Cape Palliser and off the Wairarapa coast but there is sufficient activity for shipping navigation to be an issue for marine energy projects.

There are no designated shipping lanes in the Wellington region, although there is a Voluntary Code For Vessels Carrying Oil Or Other Harmful Liquid Substances In Bulk (Maritime NZ, 2006). The code has some advisory routes for entry into Wellington Harbour. These are based on safe operational behaviours and general '*rules of the road*':

> **From the East:** vessels must keep at least 5 nautical miles off Cape Palliser and 3 nautical miles off Baring Head until due south of the harbour entrance.
>
> **From the West:** vessels must pass midway between the Brothers and Fisherman's Rock, then at least 4 nautical miles off Cape Terawhiti, thence 4 nautical miles off Karori Rock.

There is also a designated pilot boarding station for vessels requiring a pilot. The relatively large number of ferries and other vessels not requiring pilots indicate that vessels unfamiliar with the area should take care in the area of the harbour. There are also advisory notes for vessels departing Wellington Harbour. More details can be found in the Maritime NZ publication and the NZ hydrographic chart for Wellington Harbour (Figure 7.6). Maritime NZ does collect ship route tracking data and they can advise project developers on conflicting navigation uses.

For marine energy projects, it is obviously vital that developers avoid areas of frequent shipping use. In law there is a presumption that any vessel can go anywhere. In practice, the area is subject to the Greater Wellington Navigation and Safety Bylaw, administered by the Greater Wellington Harbourmaster.

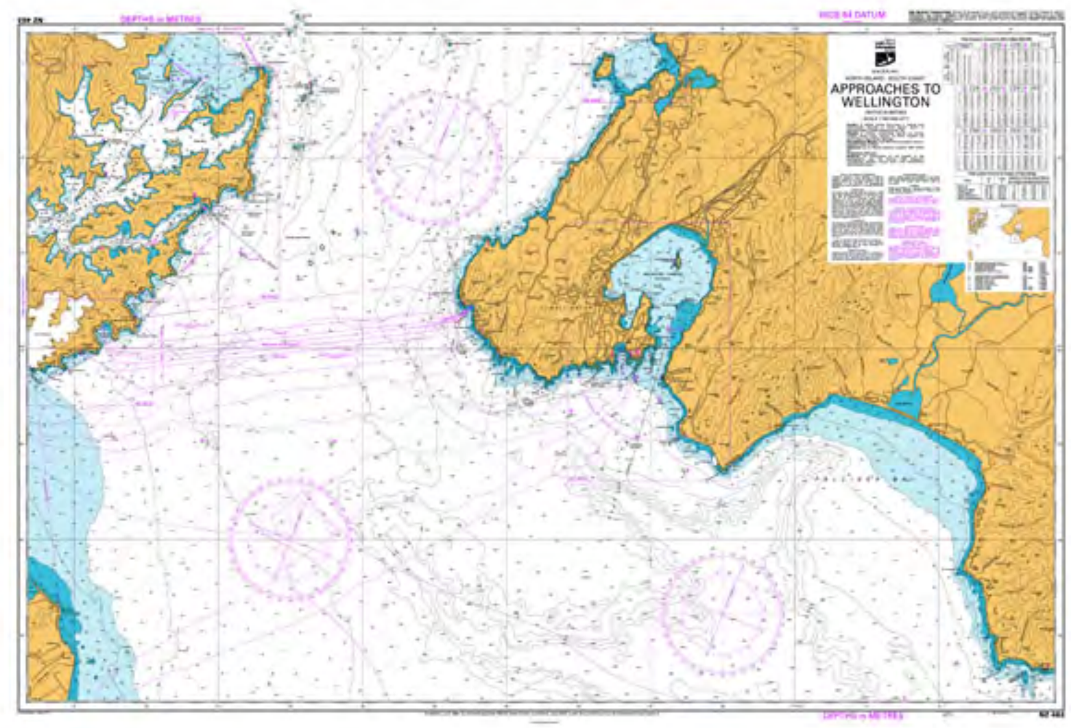


Figure 7.6: Approaches to Wellington – LINZ Chart NZ463

Copies of this and other hydrographic charts available at www.linz.govt.nz

7.4.9 Other Exclusions

There are a number of other Regional Coastal Plan constraints, which might have an impact on marine energy projects in the Wellington CMA. These include the following:

1. Mooring areas (Wellington and Porirua Harbours, Pauatahanui Inlet and Island Bay)
2. Commercial developments (Wellington Harbour)
3. Aquifer zones (Wellington Harbour)
4. Water quality classes (nearshore areas managed for water contact recreation, *i.e.,* swimming or surfing, and shellfish gathering purposes)

Maps of these areas are available on the GWRC website (www.gw.govt.nz/section866.cfm) and they are shown in Figure 7.3 (page 72). These areas are likely to present little or no difficulties to marine energy projects since the majority of them lie within Wellington Harbour, Porirua Harbour, Pauatahanui Inlet or very close to shore, in areas where marine energy projects are unlikely to be developed, particularly in the first instance.

7.5 SUMMARY

The tidal/ocean current resources of the Greater Wellington CMA present an attractive target for future marine energy investigations. Undoubtedly the mapping presented here and the proposed deployment of the prototype tidal/ocean current device by Neptune Power will raise interest in the Wellington CMA. The Wellington CMA represents the best tidal/ocean current resource mapped in this study, taking into account other factors such as access to transmission infrastructure and markets. It is likely that other projects will be proposed here in due course.

Modelling of wave resources during the course of the present study indicates that these are not so attractive. The results for the Wairarapa location are probably analogous to the results that might have been obtained in Cook Strait or the south coast of Wellington. It is likely that other areas will be developed first, before the Wellington CMA becomes attractive.

Significant constraints to marine energy projects will have to be overcome or addressed by project developers. These include intrinsic issues, such as site selection, device survival and absence of information on environmental effects, and extrinsic issues, such as competing uses, lack of information on shipping movements and whale migration. However, there is an even-handed regulatory environment and information gained from the Neptune Power prototype deployment will be directly useful to both developers and regulators. The Wellington CMA is likely to be one of the first areas to see larger-scale tidal/ocean current developments in New Zealand.

BIBLIOGRAPHY

AEA, 2006. *Review and Analysis of Ocean Energy Systems Development and Supporting Policies.* AEA Energy and Environment, June 2006.

APPA, 2007. *Spanish Promotory [sic] Enterprises Vision about marine energies.* APPA presentation, 7 March 2007.

AWATEA, 2007. *Marine Energy in New Zealand.* Presentation to Electricity Commission's "Transmission to Enable Renewables" workshop, 17 December 2007.

Bellve, A.R., 2008. *Harnessing energy from sustainable marine resources.* Presentation to 2nd AWATEA conference, Wellington, 29 May 2008.

Bond Pearce, 2005. *The Path to Power: Legal and Regulatory Requirements.* Bond Pearce LLP, November 2005.

BWEA, 2006. *The Path to Power: Delivering confidence in Britain's wave and tidal stream energy industry.* BWEA and npower juice, London, July 2006.

Carcas, M., 2008. *Pelamis Update.* Presentation to All-Energy Conference, Aberdeen, Scotland, 24 May 2008.

Carnegie Corporation, 2008.

Capitalizing on the Demand for Clean Energy. Presentation to 2nd AWATEA conference, Wellington, 29 May 2008.

Clark, F., 2008. *Wind Energy in NZ – the way forward.* Presentation to NZ Wind Energy Conference, Wellington, 8 April 2008.

Couch, S. and Bryden, I.G., 2004.

The Impact of Energy Extraction on Tidal Flow Development. Supergen Marine Marec Paper:

Crest Energy, Limited, 2006.

Kaipara Harbour Marine Turbine Electricity Generation Project: Application for Resource Consents and Assessment of Environmental Effects. Auckland, July 2006.

Crest Energy Limited, 2007.

Kaipara Harbour Marine Turbine Power Generation Project: Project Update and Further Information Pursuant to Section 92 RMA. Auckland, July 2007.

Crest Energy Limited, 2008.

Crest Energy's Progress in the Kaipara Harbour Project. Presentation to 2nd AWATEA conference, Wellington, 29 May 2008.

DoC, 2008. *Wonderful Whale-ington.* Department of Conservation, Wellington, 2008; www.doc.govt.nz.

DTI, 2005. *Planning and Consents for Marine Renewables* Department of Trade and Industry, London, November 2005.

East Harbour, 2003. **S***outhland Regional Energy Assessment.* Consultant report for Venture Southland, East Harbour Management Services Ltd, August 2003.

EMEC, 2008. *Wave Energy Devices & Tidal Energy Devices.* www.emec.org.uk.

EPRI, 2003. *Guidelines for Preliminary Estimation of Power Production by Offshore Wave Energy Conversion Devices.* Electric Power Research Institute report E21 EPRI-WP-US-001, 22 December 2003.

EPRI, 2004. *Offshore Wave Power in the US: Environmental Issues.* Electric Power Research Institute report E21 Global EPRI - 007 - US, 21 December 2004.

EREC, 2004. *Renewable Energy Policy Review: Portugal.* European Renewable Energy Council report. Brussels, May 2004.

Falnes, J., 2002a. *Ocean Waves and Oscillating Systems: Linear Interactions including Wave Energy Conversion.* Cambridge University Press, 2002.

Falnes, J., 2002b. *Optimum Control of Oscillation of Wave Energy Converters,* International Journal of Offshore and Polar Engineering, June 2002.

Froude, A., 2004. *Area-based restrictions in the New Zealand marine environment.* Department of Conservation, Wellington, 2004.

Gibbs, N. & Childerhouse, S., (2000).

Humpback whales around New Zealand. Conservation Advisory Science Notes, 287:1 - 32.

GWRC, 2008. *[Neptune Power] Non-notified resource consent application report and decision.* Greater Wellington Regional Council, published report, 10 April 2008.

IEA:OES, 2008 *Annual Report 2007.* International Energy Agency – Ocean Energy Systems Executive Committee, Paris, April 2008.

IRD, 2008. *Currency rates 2008 – mid-month.* Inland Revenue Department, Wellington (mid-March 2008).

L.E.K., 2006. *Policy Framework for Renewables.* L.E.K. Consulting LLP & the Carbon Trust. London, July 2006.

MEG, 2004. *Harnessing Scotland's Marine Energy Potential.* Marine Energy Group (MEG) report 2004. Edinburgh, July 2004.

Maritime NZ, 2006. *Shipping Routes Around the New Zealand Coast.* Maritime New Zealand, Wellington, 2006.

MEG, 2004. *Harnessing Scotland's Marine Energy Potential.* Marine Energy Group of the Forum for Renewable Energy Development in Scotland.

Meridian Energy, 2007.

Marine Energy Information Sheet. Meridian Energy, Wellington, March 2007.

Meridian Energy, 2008.

Marine Energy Information Sheet. Meridian Energy, Wellington, March 2008.

Natural Systems HV, 2006.

Presentation to Distributed Generation Symposium, Christchurch, June 2006.

Neptune Power, 2007.

Neptune Power Project. Presentation to Electricity Commission's "Transmission to Enable Renewables" workshop, 17 December 2007.

Neumann, F., Brito-Melo, A., Didier, E. and Sarmento, A., 2007.

Pico OWC Recovery Project: Recent Activities and Performance Data. Proceedings of the 2007 European Wave and Tidal Energy Conference, Porto, 11-14 September 2007.

NZBCSD, 2006. *Energy 2050: Powering Our Future.* Wellington, 2006.

New Zealand Government, 2007a.

New Zealand Energy Strategy to 2050: Powering Our Future. Wellington, 11 October 2007.

New Zealand Government, 2007b.

New Zealand Energy Efficiency and Conservation Strategy: Making it Happen. Wellington, 11 October 2007.

New Zealand Government, 2007c.

The Framework for a New Zealand Emissions Trading Scheme. Wellington, 11 October 2007.

New Zealand Government, 2007d.

New Zealand Marine Energy Deployment Fund: Fund Definition Document. Wellington, 17 October 2007.

NZWEA, 2008. *Current wind farms, projects under construction, projects for which resource consents have been applied and potential future developments.*

http://www.windenergy.org.nz/FAQ/proj_dom.htm

PB Power, 2006. *Emerging Supply-side Energy Technologies.* Consultant report for Ministry of Economic Development, Wellington, 25 July 2006.

Power Projects Limited, 2005a.

Marine Energy: Summary of Current Developments and Outlook for New Zealand. Consultant report for EECA, Wellington, 18 May 2005.

Power Projects Limited, 2005b.

Sustainable Energy Technology Collaboration in Harnessing Ocean Energy. Consultant report for MED, Wellington, 20 July 2005.

Power Projects Limited, 2007.

Comparative Analysis of Point Absorber Devices. Confidential internal report. Wellington, April 2007.

RAB, 2008. *Marine Renewables: current status and implications for R & D funding and the Marine Energy Deployment Fund.* Renewables Advisory Board, RAB (2007) 0182; URN 08/566.

REN21, 2008. *Renewables 2007: Global Status Report.* Renewable Energy Policy Network. www.ren21.net, 2008.

Scottish Enterprise, 2005.

Marine Renewable (Wave and Tidal) Opportunity Review: Introduction to the Marine Renewable Sector. Report by Scottish Enterprise, December 2005.

Scottish Executive, 2006.

Matching Renewable Electricity Generation with Demand. University of Edinburgh report commissioned by the Scottish Executive, February 2006.

SDC, 2007. *Turning the Tide: Tidal Power in the UK*. Sustainable Development Commission, London.

SKM, 2006-08. *Regional Renewable Energy Assessments*. 12 Consultants' reports for EECA, Auckland, 2006-08.

Statkraft, 2006. *Osmotic Power: A Huge Renewable Energy Resource*. Statkraft Development AB, Oslo, Norway.

Stevens, C.; Smith, M.; Gorman, R.; Popinet, S. and Walters, R. 2007.

Marine Renewable Energy Research in New Zealand: A Multi-scale Perspective of Resources and Impacts. Australasian Coasts and Ports Conference, Melbourne Australia.

Transpower & Ministry of Transport, 2006.

Cook Strait Submarine Cable Protection Zone. Information brochure, Transpower and Ministry of Transport, Wellington, May 2006.

Triodos Bank, 2008. *Marine Power Lags Wind by Only 5 Years*.

Reuters News Service report cited in http://www.planetark.com/dailynewsstory.cfm/newsid/48674/story.htm

Willis, T.J. and Handley, S.J., 2008.

Projected effects of submarine turbines on marine fauna in Cook Strait. NIWA Client Report NEL2008-001.

WWEA, 2008.	*Wind turbines generate more than 1% of the global electricity*. World Wind Energy press release, Bonn, 21 February 2008.
Wright, M., 2008.	*The Development of the 'SeaGen' Tidal Stream Generator: Installation*. Presentation to All-Energy Conference, Aberdeen, Scotland, 24 May 2008.

APPENDIX A: CONTRACT, METHODOLOGY AND FORECASTS

APPENDIX A: CONTRACT, METHODOLOGY AND FORECASTS

A.1 CONTRACT AND WORKING ARRANGEMENTS

Dr. Bruce Smith of the Electricity Commission (EC) initially commissioned the research work but once in progress, Power Projects Limited proposed a consortium approach, including the Energy Efficiency and Conservation Authority (EECA). Once agreed between the parties, PPL contracted for this work under EC contract T60. Power Projects Limited then sub-contracted MetOcean Solutions Limited to undertake the resource reviews, integration with device performance characteristics, site-specific and regional marine resource mapping.

Dr. John Huckerby and Mr. David Findlay of Power Projects Limited in Wellington undertook their share of the work between 14 February and 30 June 2008, whilst Dr. Peter McComb, Dr. David Johnson and Dr. Brett Beamsley of MetOcean Solutions Limited in New Plymouth and Raglan between 4 March and 30 June 2008. There was close co-operation between the two companies to ensure that performance information from individual devices was integrated with area-specific wave and tidal resource assessments.

A.2 METHODOLOGY AND DATA SOURCES

Power Projects completed the overall report but specifically Parts 2 and 3 with comments by MetOcean Solutions. Parts 2 and 3 use only publicly available sources of information and knowledge by Power Projects Limited through its international contacts and involvement with the International Energy Agency's Ocean Energy Systems Implementing Agreement (IEA:OES-IA). Power Projects has attended three of the last four IEA:OES Executive meetings, contracted through the Aotearoa Wave and Tidal Energy Association (AWATEA). The IEA:OES-IA is dedicated to disseminating an understanding of international developments in marine energy.

Various recent Government publications have been used, including:

- Energy Outlook to 2030 (MED, 2006)
- New Zealand Energy Strategies (NZ Government, 2007a & b)
- Emissions Trading Scheme (NZ Government, 2007c)
- Energy Data Files (MED, 2005 - 7).

International publications by the US-based Electric Power Research Institute (EPRI, 2003) and two UK-based organizations, the Carbon Trust (2006) and, most recently, the Sustainable Development Commission (SDC, 2007) have proven very useful. Finally a review by the Renewables Advisory Board in the United Kingdom provided valuable evidence on the effects and benefits of UK Government funding for marine energy projects there (RAB, 2008).

Part 4 summarizes the wave and tidal energy resource assessments that have been undertaken in this study:

1. Quantifies the wave and tidal stream (both estuarine/harbour and open ocean) resources, and
2. Specifically models two tidal stream areas and six wave energy areas, chosen for a range of wave conditions,
3. Each one of the wave energy sites has been further analyzed by simulating the installation of three generic wave energy converters or two tidal stream energy converters to derive energy conversion and production in each area.

Appendices B & C describe the methodology and technical details of the resource and device modelling, which underpin the resources assessments.

Part 5 was the most difficult to complete, because there is no current public inventory of potential projects, as there are for wind, hydro and geothermal generation. It is therefore not possible to analyze an existing inventory and make comparative judgments about the potential of each project. With the exception of a small number of proposed projects outlined in media articles, there has not been any systematic review of the domestic potential for marine energy, other than '*technically feasible*' resource assessments (*e.g.,* SKM, 2006 - 2008).

Part 6 integrates marine energy converter information and areal resource assessments with constraints facing any marine energy projects. The Wellington CMA is used a case study to set out the opportunities for and constraints on any intending marine energy project development in this area. The case study serves as a general guide to the development of any marine energy project in New Zealand, although the opportunities and constraints will differ between sites.

A.2.1 Forecasting

This report is also a speculative forecast of the future of marine energy in New Zealand. As far as possible it is a factual and objective account of international and domestic devices and deployments to date. Forecasting future developments is obviously more difficult, with the possibilities ranging from a vibrant domestic industry supplying local projects and exporting to international markets to a stillborn renaissance, similar to the development of first-generation marine energy devices in the 1970s. It is notable that the New Zealand Electricity Department and its successor, the Electricity Corporation of New Zealand, conducted reasonably extensive research on the potential for marine energy in the 1980s and early 1990s. PPL has previously sought access to reports produced by these organizations but access has been declined.

With respect to individual devices Power Projects Limited has based its conclusions on future development and New Zealand deployment of these devices on the past history and current status of device developments. Absence of or low ranking of any device mentioned in this report is not intended to criticize or disadvantage these devices. Devices and companies mature at changing rates and their relative competitive positions change over time. The current clear leaders could be overtaken as device designs converge to single niche designs, just as the designs of the 1970s have been overtaken by Pelamis, SeaGen and the other devices described here. With so many devices at such different stages of development, it is impossible to forecast the future accurately.

Notwithstanding the above, Power Projects Limited is confident that marine energy will become an important generation source in future. The first 2 kW device was deployed in December 2006 (the WET-NZ device in Pegasus Bay in Christchurch) and bigger devices are likely to be deployed as a result of encouragement from the Marine Energy Deployment Fund (NZ Government, 2007d). The first device was recently moved to Wellington Harbour (May 2008) and a second 2 kW device will soon be deployed in Pegasus Bay.

A.2.2 Cost Estimates

Cost figures, including cost ratios, in this report are cited first as the cost or ratio cited in each reference used (*i.e.,* the overseas currency in money of the day terms). The figures are then directly converted to New Zealand dollar (without any adjustment for time) at the 2008 mid-month exchange rate for each currency (IRD, 2008):

NZ$: US$ = 0.7540
NZ$: £ = 0.3769
NZ$: Euro = 0.5385
NZ$: AU$ = 0.8764

A.2.3 Acknowledgements

Power Projects would like to acknowledge the following:

- MetOcean Solutions Limited for their excellent mapping work and close co-operation in the production of this document
- David Findlay for his work on the wave and tidal stream device modelling
- The various device developers for the information that they provided via their websites and presentations
- At Greater Wellington Regional Council, Piotr Swiercynski (Policy Advisor) and Mike Pryce (Wellington Harbourmaster) for advice and feedback on the Wellington constraints to marine energy projects; Nick Page (GIS Officer) for maps and constraints data in GIS format
- Alan Sheppard and Nici Gibbs at the Seafood Industry Council for advice on fishing issues in the Wellington CMA and further afield
- Evan Perry of EMS and Andy Wilson of Vector for GIS information on the Transpower Grid and Vector distribution network layouts, respectively
- Steve Smith of Department of Conservation and Anton Van Helden of Te Papa Tongarewa for information on whale migration, sightings and strandings

APPENDIX B: MODELLING SINGLE POINT ABSORBER DEVICES

APPENDIX B: MODELLING SINGLE POINT ABSORBERS

B.1 INTRODUCTION

The Pelamis P750 wave energy converter is only one of a wide variety of devices currently under development. It is, however, the only one for which a power spectrum has been published. In the absence of published data for other WECs, a power spectrum for a generic single point absorber (SPA) was created to demonstate how the performance from different devices might be compared. The power spectrum, developed in the following section, is not intended to be representative of any particular device, it is simply illustrative of the performance of a generic single point absorber.

WECs convert the energy flux within an incident wave field into useful energy. Often the most convenient form of 'useful' energy end product is electricity. However, in order to produce electricity of acceptable quantity and quality, the device will have to perform a sequence of energy conversions

The energy from the wave field interacts with a floating or active body (or bodies), which dynamically responds and, consequently, stores mechanical energy. The kinetic and potential energy in the waves, expressed as motion vectors of heave, surge and pitch, can be converted to electricity via several intermediate steps, *e.g.,* kinetic & potential energy to mechanical energy to magnetic energy to electrical energy.

The wave power, or energy flux, in a wave field can be found from the equation:

Equation 1 $$P = \frac{\rho g^2}{32\pi} H_{sig}^2 T \approx (1.0\frac{kW}{m^3 \cdot s}) H_{sig}^2 T$$

Equation 1 gives a value of the energy flux per metre of wave front. A well-designed wave energy device will aim to maximize its capture width and therefore its yield (*i.e.,* its coupling efficiency to the wave). For a terminator device (such as an oscillating water column device), the maximum theoretical energy capture is approximately equal to the physical width of the device, measured perpendicular to the direction of wave propagation. By contrast, however, Falnes (2002B & C) has shown that *"the maximum energy which may be absorbed by a heaving axi-symmetric body is equal to the wave energy transported by the incident wave front of width equal to the wavelength divided by 2π".* A single point absorber WEC is roughly equivalent to a heaving axi-symmetric body. This result may be termed the maximum absorption width $d_{MAX.}$

Equation 1 $$d_{MAX} = \frac{\lambda}{2\pi}$$

Where λ is the wavelength, which is related to the period through the dispersion relationship. For deepwater the dispersion relationship is given by:

Equation 2 $$\lambda = \frac{gT^2}{2\pi}$$

Falnes also derived an equation for the upper bound of the Power-to-Volume ratio for a WEC. This is summarized as:

Equation 3 $$\frac{P}{V} < \frac{\pi \rho g H}{4T}$$

where V is the volume of the absorber, and H and T and the wave height and period respectively.

These equations can be combined to calculate a theoretical maximum power capture for a particular axi-symmetric point absorber, moving in one degree of freedom (i.e., heave), given the volume of the device, the wave period and wave height, substituting the significant wave height, H_{sig} for spectral sea states ().

Equation 4

$$P_{Max} \le \begin{cases} \dfrac{\rho g^3 H^2 T^3}{128\pi^3} \; IF \; \dfrac{\rho g^3 H^2 T^3}{128\pi^3} \le \dfrac{V\pi\rho g H}{4T} \\ \dfrac{V\pi\rho g H}{4T} \; IF \; \dfrac{\rho g^3 H^2 T^3}{128\pi^3} \ge \dfrac{V\pi\rho g H}{4T} \end{cases}$$

The relationship represented by this equation is theoretical and, whilst it can be used to demonstrate general trends, it is unlikely that a real device will ever approach this sort of performance. The reasons for the disparity between theoretical and actual performance are threefold:

1. Any device will suffer from inefficiencies at each energy conversion and transmission stage and,
2. Point absorbers are essentially resonant devices, which - for optimum
3. Hydrodynamic performance - must fulfil a set of criteria defining their dynamic interaction with the wave field.
4. **Equation 6** (upper bound of the power-to-weight ratio) approaches equality as the volume goes to zero. This is clearly unrealistic.

B.2 RESONANCE

Power is the product of force and velocity. For optimal power capture, one requirement is that the force applied to the power take off device must be in phase with the velocity of the device. When this condition is met the device resonates with the wave field. A surface-piercing free-floating body is subject to a natural oscillation in heave, whose period is governed primarily by the relationship between its mass and its volume (hydrostatic spring). One condition for resonant behaviour is that the natural period of the device is the same as that of the incident waves. This is a very simplified discussion of an involved subject but it is sufficient for this analysis.

The relative absorbed-power response can be calculated from Equation 6.

Equation 5

$$RAPS = \frac{1}{1 + (\omega_0 / 2\delta)^2 (\omega / \omega_0 - \omega_0 / \omega)^2}$$

In the above equation, the parameters, ω and ω_0 refer to the incident frequency and natural frequency of the device respectively. The system damping (from the power take off system and viscous effects) is represented by the δ term.

Figure B1 shows how the response of a point absorber varies with the period of the incoming waves. The value of the response has been non-dimensionalized. In this instance the device has a natural period of 8 seconds and its response is narrow banded, *i.e.,* it exhibits reasonable performance across a narrow band of periods.

A curve similar to the one above was used to modify the ideal performance characteristics and to take into account the frequency sensitivity of the device.

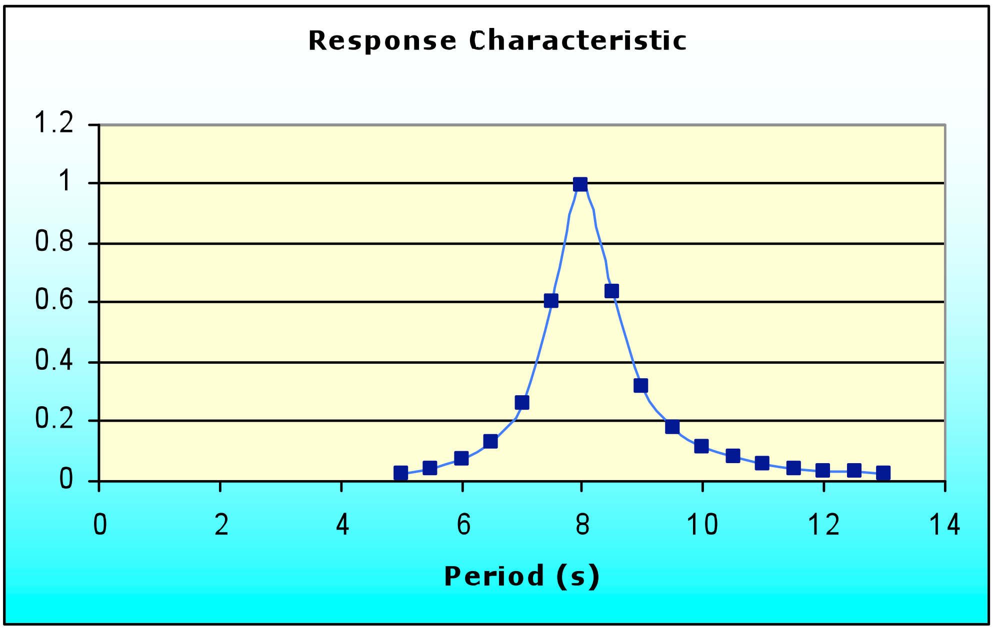


Figure B1: Typical Response for a Single Point Absorber

B.3 POWER TRAIN EFFICIENCY

Inefficiencies within the power take off system of the device will also vary depending upon the operating conditions, for instance a hydraulic pump or motor as used in a transmission system, will have an optimum operating point that will most likely depend on both the pressure and the flow rate within the system. Its efficiency may well drop off dramatically as it deviates from this point. Similarly other hydraulic devices such as Pelton wheel turbines and electrical generators will have performance characteristics that will vary with the operating conditions while hydraulic transmissions will have a pipe loss that varies with the square of the flow rate and the pressure component. Electrical conversion units such as generator sets, transformers and power conditioning units will all demonstrate a power loss (usually manifested as heat) whose magnitude will depend on the instantaneous operating conditions.

The configuration of components within the power train, and the influence of the performance characteristics of these components upon the performance of the overall unit is, by its nature, device specific, and in the interests of maintaining a generic approach, no attempt has been made here to include the sensitivity of the power train efficiency to the wave height and period within the operating characteristics of the generic point absorber. As a compromise a flat power train efficiency, across both wave height and period, was used to imply the impact of these inefficiencies while preserving the original trends.

Equation 6 $$P_{\mathrm{mod}} = \eta_{PTO} * RAPS * P_{Max}$$

B.4 DEVICE RATING

Finally, wave power machines must include the facility to 'rate' their developed power in order to avoid overloading the electrical and mechanical components within the drive train. This feature has been included within the generic point absorber model by flattening off the power matrix above a rated value. See **Equation 7**.

Equation 7 $$P_{mat} = \left\{ \begin{matrix} P_{\mathrm{mod}} \\ P_{rat} \end{matrix} \right\} \left\{ \begin{matrix} P_{Mod} \le P_{rat} \\ Otherwise \end{matrix} \right.$$

B.5 ASSUMPTIONS

This approach assumes more than it can rely upon. It therefore can only be taken as a first pass attempt to identify trends within the confines of basic wave power theory. Assumptions taken include:

- Linear wave theory, and the deepwater dispersion relationship
- Flat efficiency characteristics for all power conversion and transmission devices.
- Strict resonant behaviour of the absorber device
- Damping, and gross efficiency data.
- Potential flow theory – no viscous hydrodynamic component.

These assumptions are justified by the nature of the report. The onus remains upon device developers, and possibly the academic community, to produce verifiable device characteristics, and, in the absence of these, a simplified attempt was made to predict general trends and representative characteristic curves. It is understood that a full study of these phenomena is beyond both the scope of this report.

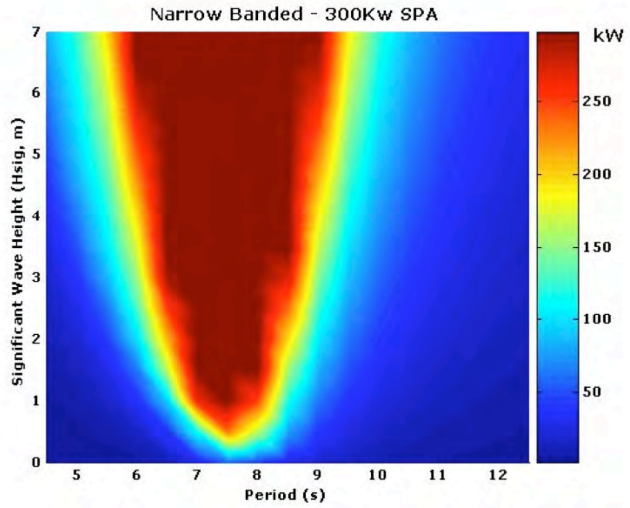
A full analysis of the performance characteristics of a wave power device is an involved process that will most likely require hydrodynamic analysis (using a potential flow solver) to determine the hydrodynamic properties of the active body. It may also require a more detailed computational fluid dynamic analysis of key elements, or indeed the device itself. A separate mooring analysis is generally required to account for the – often non-linear – interaction with the mooring attachment, and a dynamic model of the power take off and control systems will all have to be integrated holistically to allow for complete specification of the device performance. Much of this work is numerical in nature, and sufficiently involved to require both extensive computing resources and the judicious application of assumptions.

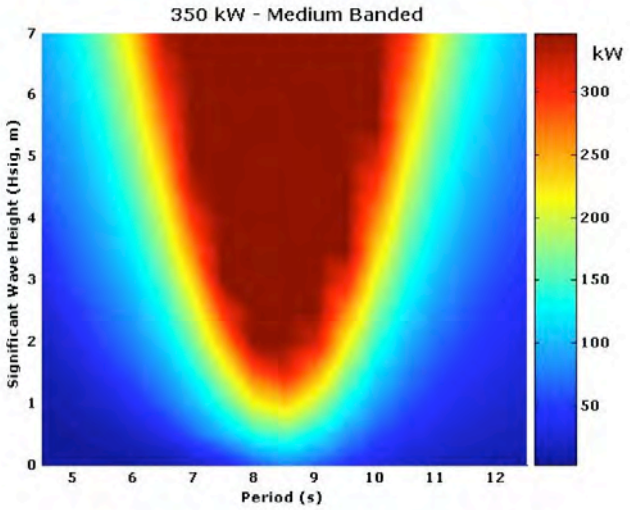
B.6 RESULTS

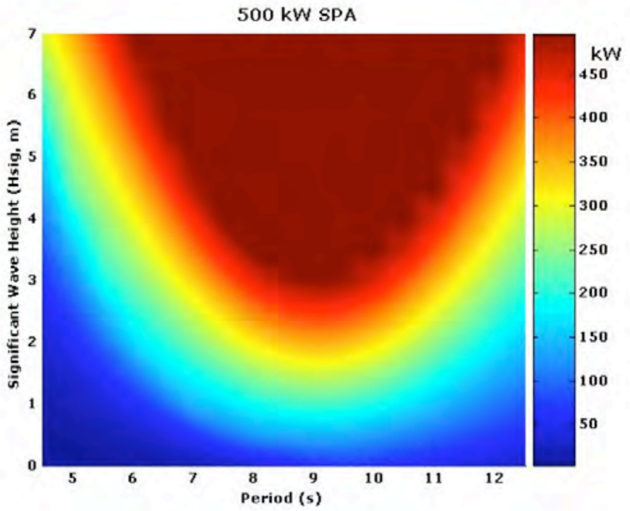
A number of figures are reproduced here showing the resulting power matrices for a number of hypothetical point absorber devices. The input characteristics are shown in Table B1 and Figures B2 to B4.

Banding	Narrow	Medium	Broad
Rating (kW)	300	350	500
Natural Period (secs)	8	9	10
Damping	0.01	0.015	0.03
Volume (m^3)	472	301	445
Efficiency (%)	60	60	40

Table B1: Properties of Modelled Single Point Absorbers Wave Energy Converters



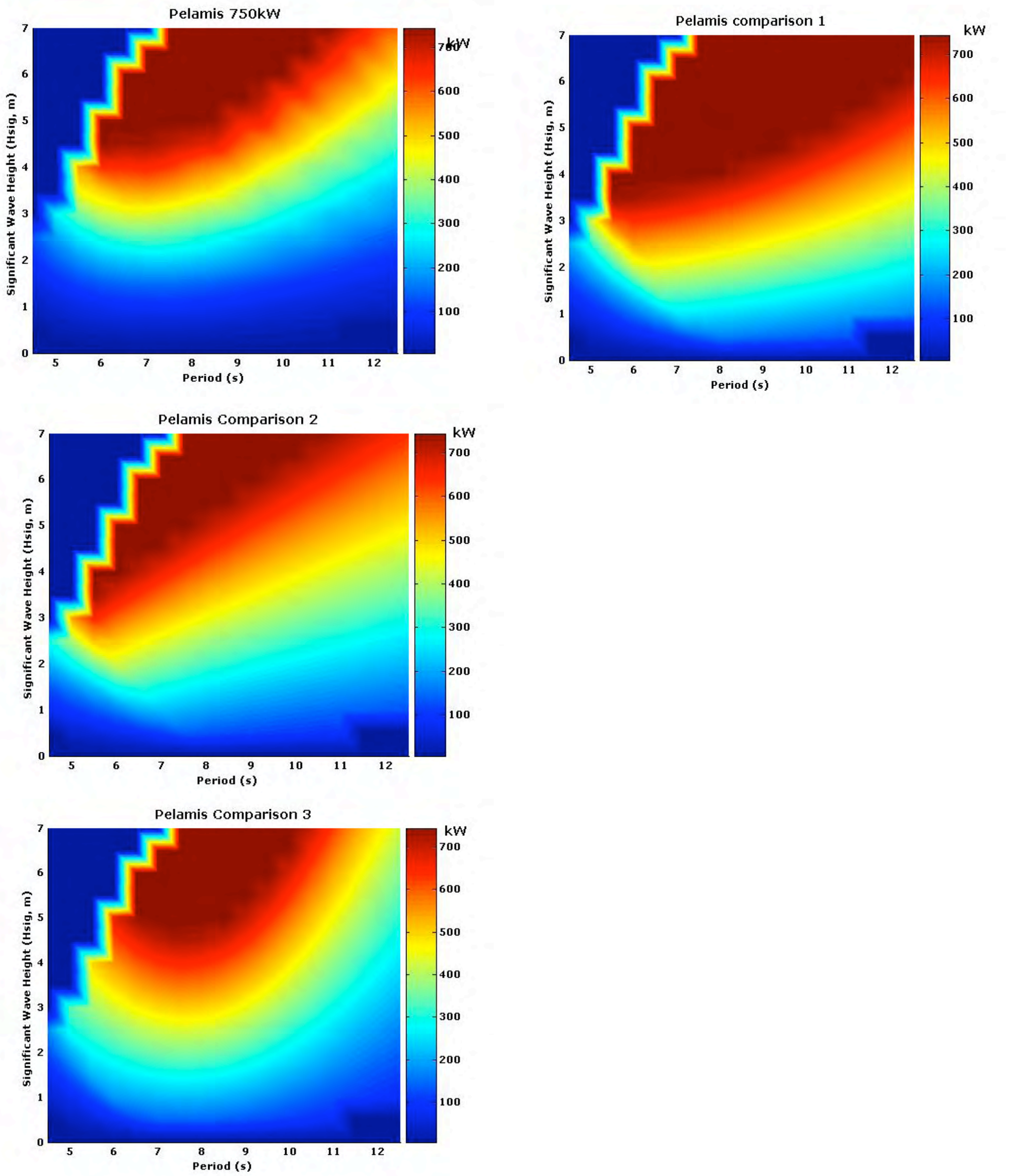




Figures B2 – B4: Power Matrices for Modelled Single Point Absorbers

B.7 COMPARISON WITH PUBLISHED PELAMIS RESULTS

It is interesting to compare the power matrices produced through this method and those generated thorough more sophisticated modelling and testing. To this end, the published 750 KW Pelamis spectrum (Figure B5) is shown alongside several attempted correlations (Figures B5 – B8).



Figures B5 – B8: Comparison of Pelamis spectrum with Modelled Spectra

Wide bandwidth devices most closely replicate the Pelamis spectrum (compare Figures B5 and B8) but the exact matrices are difficult to match exactly. The stepped effect in the high frequency, large wave-height area of each matrix, is present in the published results and replicated in the present modelling. This stepped effect corresponds to a high frequency breaking wave region, which is either unrealistic or sufficiently detrimental to the performance of the device to require all developed power to be shed (Table B2).

	Comparison 1	Comparison 2	Comparison 3
Rating (kW)	750	750	750
Natural Period (secs)	11	11	9
Damping	0.1	2.0	0.05
Volume (m^3)	471	402	262
Efficiency (%)	40	35	60

Table B2: Comparison of Properties of Pelamis P750 with Modelled Results

APPENDIX C: “MARINE ENERGY RESOURCES: OCEAN WAVE AND TIDAL CURRENT RESOURCES IN NEW ZEALAND”

MARINE ENERGY RESOURCES

Ocean wave and tidal current resources in New Zealand

Prepared for the Energy Efficiency and Conservation Authority and
the Electricity Commission of New Zealand

May 2008

MetOcean Solutions Ltd
www.metocean.co.nz

Suite 3, 17 Nobs Line, PO Box 441
New Plymouth, New Zealand
T: 64-6-7585035 E: enquires@metocean.co.nz

Report Status

Version	Date	Status	Approved By:
RevA	26/06/2008	Draft	McComb
RevB	29/06/2008	Draft for review	Johnson
Rev0	24/07/2008	Updated draft	McComb
Rev1	22/08/2008	Approved for release	McComb

It is the responsibility of the reader to verify the currency of the version number of this report. This report was prepared by D. Johnson, P. McComb, B. Beamsley and R. Zyngfogel.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

The Energy Efficiency and Conservation Authority (EECA) and the Electricity Commission (EC) of New Zealand have appointed Power Projects Ltd (PPL) to provide a summary of the current marine energy developments and the intermediate-range outlook for New Zealand. Specifically, the objective is to provide advice on the potential development of marine energy generation to assist with the planning for future transmission and generation investments. MetOcean Solutions Ltd (MSL) has been subcontracted by PPL to provide an assessment of the open-coast wave and tidal energy resources.

The aim of this report is to provide a framework to assess potential for deployment of marine energy devices, prior to the industry maturing and sufficient data becoming available for objective evaluation on generator performance and operation criteria (including opex-capex issues). As improved device and economic data becomes available, it is envisaged that this report will provide a basis for subsequent analysis of the applicability of the improving technology.

1.1 Scope of work

The scope of this report is to:

- Identify the spatial distribution of the open-coast marine energy resources in New Zealand (waves and tidal currents);
- Provide a quantitative description of the open-coast tidal resources, including a detailed examination of two primary locations (Cook Strait and Foveaux Strait);
- Provide a quantitative description of the open-coast wave energy resources, including detailed examination of six example locations that effectively bracket the typical wave energy range, and

- Simulate the likely wave energy conversion using three generic wave power devices (based on the manufacturer's specifications where available).

The scope is achieved using the following methods:

- Undertake a region-scale 10-year numerical wave hindcast for New Zealand waters;
- Undertake depth-averaged tidal current modelling of New Zealand waters, with detailed modelling of the Cook Strait and Foveaux Strait regions;
- Produce maps of the open-coast wave and tidal energy resources;
- Produce maps of the wave statistics and power output from three generic devices;
- Undertake a time-series simulation of the wave power output from the three devices at six discrete locations, and
- Characterise the ocean current regime at potential Cook Strait and Foveaux Strait tidal power locations and simulate the power output with a generic current energy conversion device.

Specific deliverables include:

- Summary maps of the open-coast tidal resource, wave climate, potential wave power, and energy output for generic wave conversion devices.
- Detailed analysis of two potential tidal energy regions and six wave energy sites, considering probable power output and seasonal variability.

1.2 Report structure

This report is structured as follows. The data sources used to characterise the wave and tidal resources are detailed in Section 2. Wave energy definitions are presented in Section 3 and information on the conversion of tidal stream energy is presented in Section 4. Wave energy resource maps are provided in Section 5, and more detailed site assessments for wave power are included in Section 6. Open ocean tidal energy resources for New Zealand are provided in Section 7, including detailed assessments of Cook Strait and Foveaux Strait. The report findings are summarised in Section 8 and the references cited are listed in Section 9.

2 METOCEAN DATA SOURCES

2.1 Numerical hindcasting

Metocean data for the marine energy assessment have been generated using a numerical hindcasting technique, which recreates the time-series of wave conditions and tidal flow conditions.

For the wave hindcasts in this study, a NZ wide domain was used (Fig. 2.1) with a longitude/latitude grid with resolution of 0.05° by 0.05° (approximately 4.5 km by 5.4 km). Tidal current modelling was carried out on the NZ grid at a resolution of 0.06° by 0.06° (approximately 5.6 km by 6.6 km) and on two nested, high-resolution domains over the Cook Strait region (Fig 2.2) and the Foveaux Strait region (Fig. 2.3); nested grid resolutions were 0.002° by 0.002° (approximately 170 m by 230 m) and 0.004° by 0.004° (approximately 340 m by 450 m), respectively.

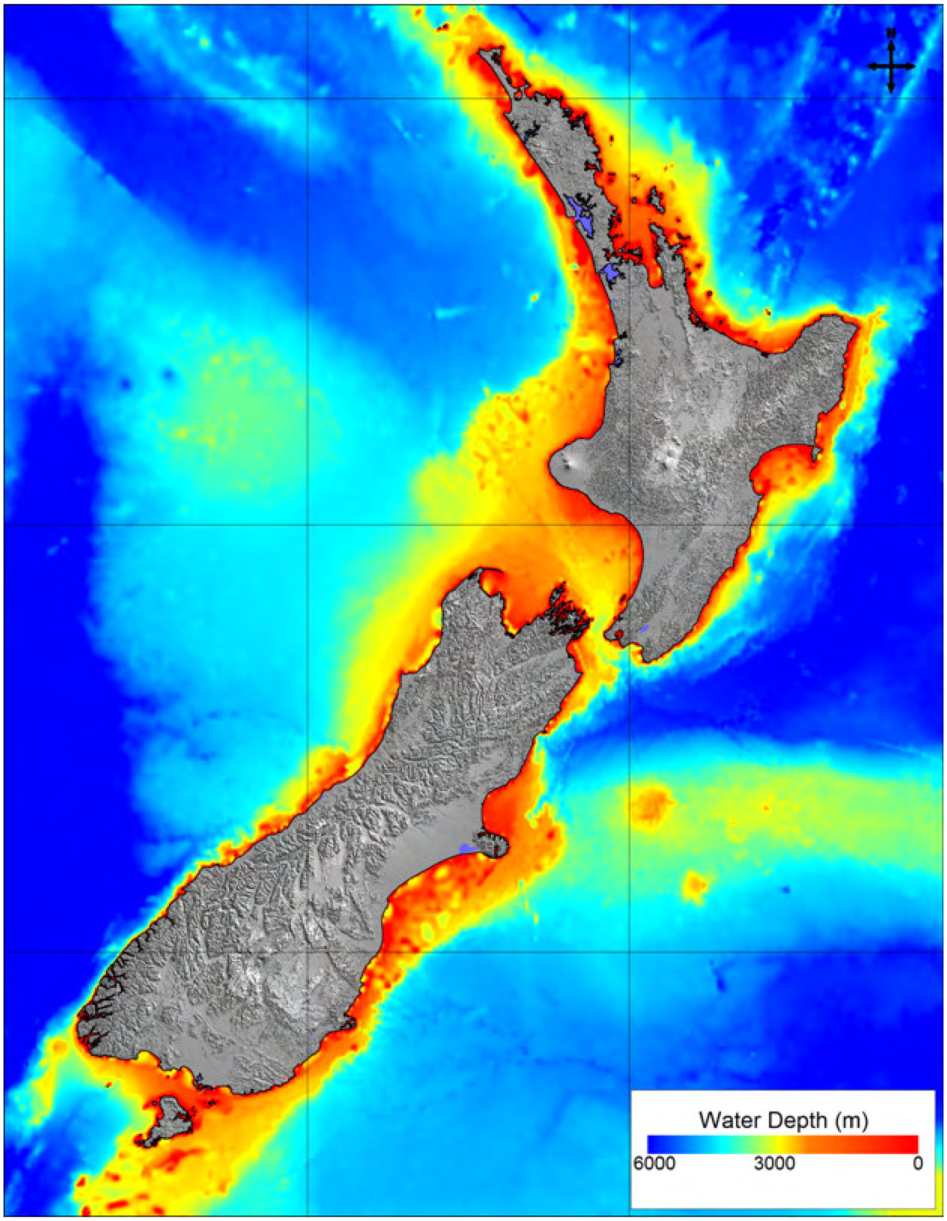


Figure 2.1 Regional-scale domain used for wave and tidal current modelling.

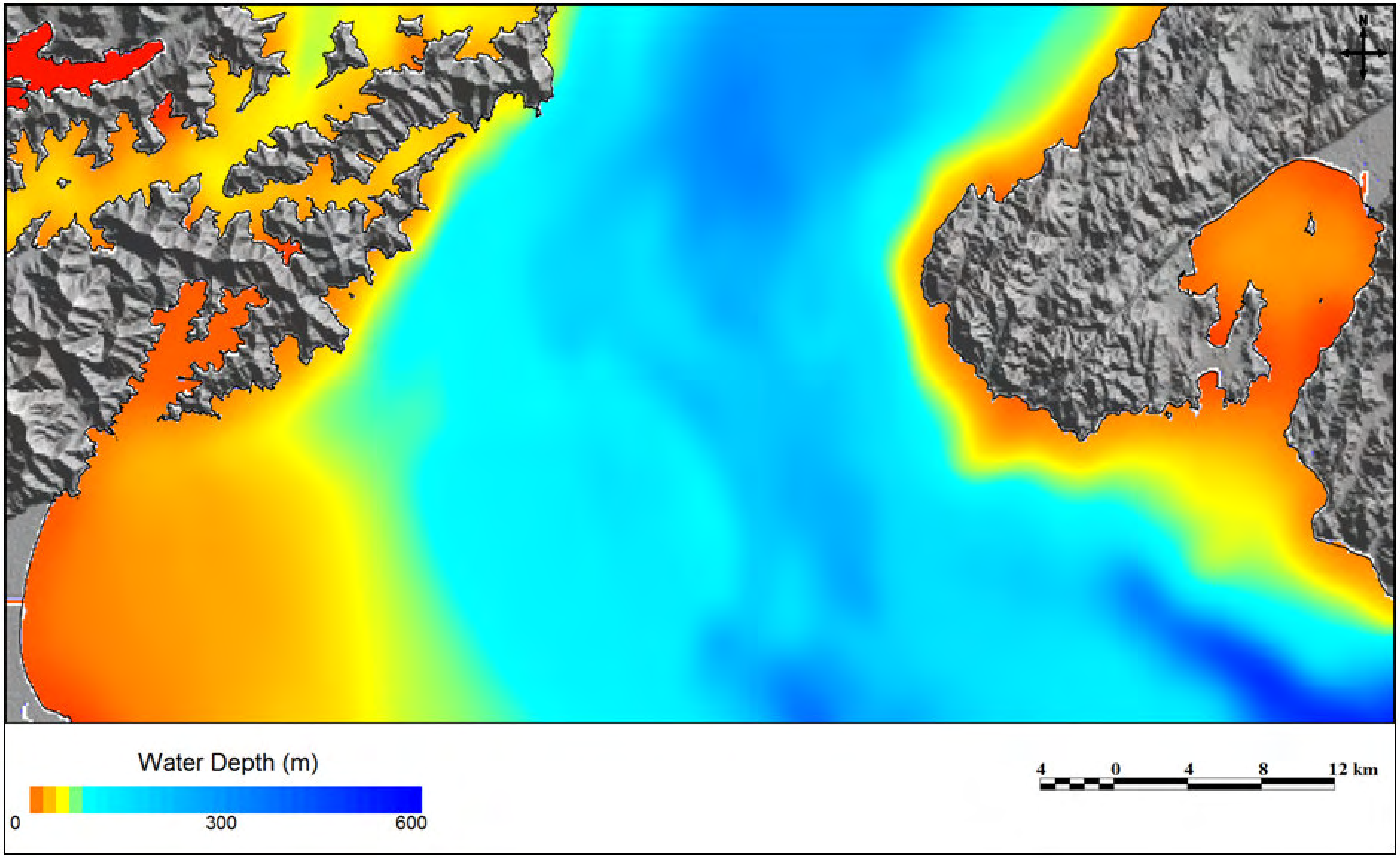


Figure 2.2 The nested high-resolution Cook Strait domain for tidal current modelling.

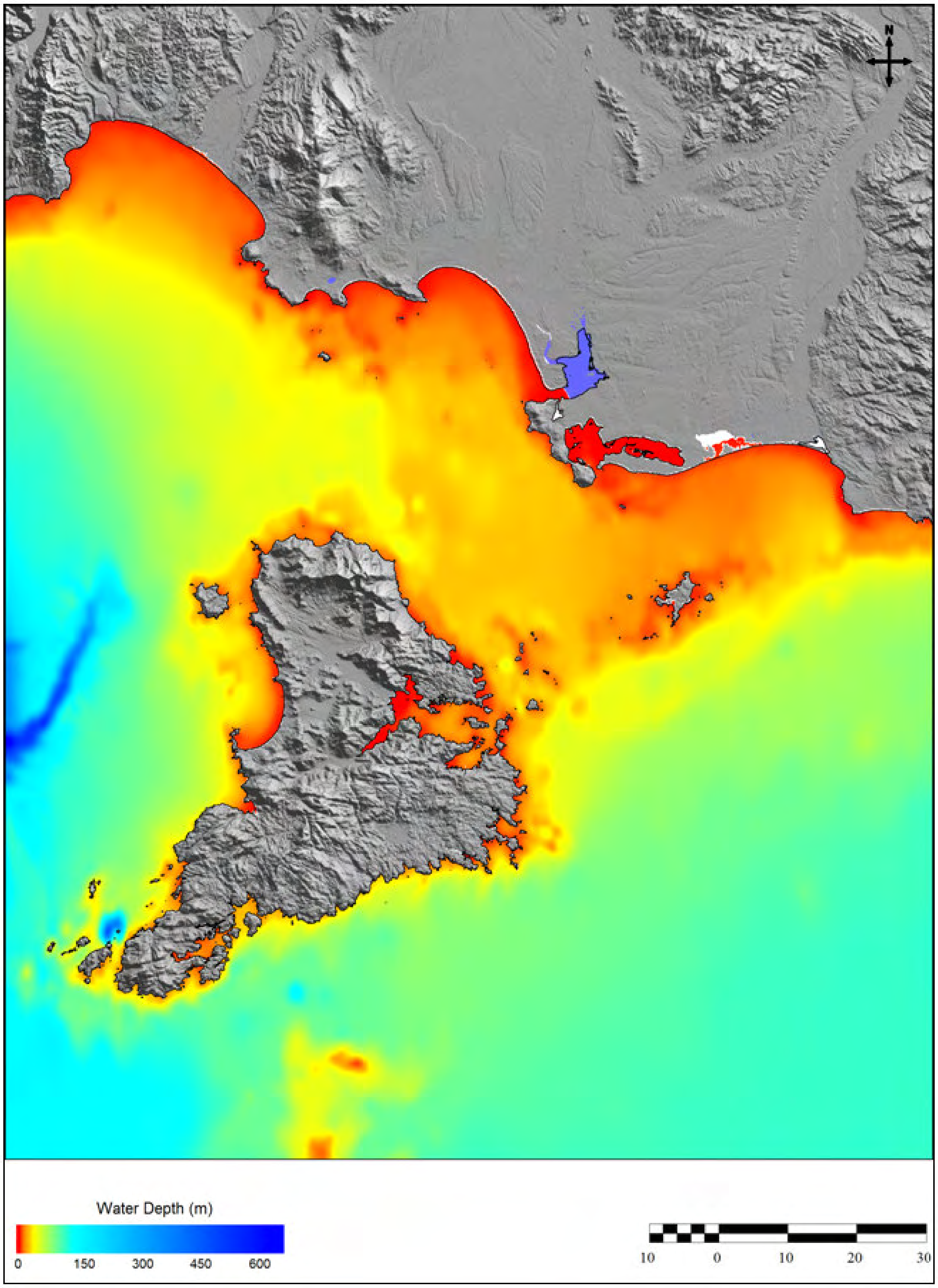


Figure 2.3 The nested high-resolution Foveaux Strait domain for tidal current modelling.

2.2 Wave hindcasting

2.2.1 Wave model

SWAN (Simulating Waves Nearshore) was used for all of the wave modelling. SWAN is a third generation ocean wave propagation model, which solves the spectral action density balance equation for wavenumber-direction spectra. This means that the growth, refraction, and decay of each component of the complete sea state, each with a specific frequency and direction, is solved, giving a complete and realistic description of the wave field as it changes in time and space. Physical processes that are simulated include the generation of waves by surface wind, dissipation by white-capping, resonant nonlinear interaction between the wave components, bottom friction and depth limited breaking. A detailed description of the model equations, parameterizations, and numerical schemes can be found in Holthuijsen *et al*. (2007). All 3rd generation physics are included. The Collins friction scheme is used for wave dissipation by bottom friction.

The solution of the wavefield is found for the non-stationary (time-stepping) mode. Boundary conditions, wind forcing and resulting solutions are all time dependent, allowing the model to capture the growth, development and decay of the wavefield.

2.2.2 Boundary conditions

The wave spectra on the open ocean boundaries of the coarse domain were obtained from the NOAA WAVEWATCH III (NWW3) solution. NWW3 is a state-of-the-art wave generation, propagation and transformation model for forecasting the evolution of directional wave energy spectra across the global oceans.

Along the open boundaries of the model domain, the primary statistical parameters of the incoming wavefield are interpolated from the NWW3 hindcast solution. Boundary spectra are then reconstructed by assuming a bi-modal Ochi-Hubble shape.

Boundary conditions for the high resolution nested grid come directly from the coarse domain.

2.2.3 Winds

The regional wind field is very important for wave generation. A spatially varying wind field was specified from a blended global wind product developed by MSL. These data are 10m wind velocity vectors in a 3-hourly gridded format at a resolution of 0.25° of longitude and latitude. The wind field is a combination of the 6-hourly Blended Sea Winds data[1] and the winds from the NWW3 hindcast. The blended data product combines the benefits of measured satellite data with the temporal resolution and continuous coverage of the modelled re-analysis.

2.2.4 Validation

The hindcast wave model outputs have been validated with wave buoy data from numerous locations around New Zealand (ranging from 10-110m depths). A validation plot for one of these locations is shown in Figure 2.4, in the highly-complex western Cook Strait. In this region there are rapidly changing wave conditions and strong gradients in local wave generation due to topographic forcing of the winds between the North and South Islands.

The wave model validation process has been undertaken as part of the engineering design specifications for the offshore oil industry, which have used the MSL hindcast data in the development of the Kupe, Pohokura, Tui and Maari Fields, plus applications in the Maui Field. Extensive peer-review of the methods and outcomes has been undertaken by a range of international experts, including marine warranty surveyors, design engineers and consulting oceanographers. The hindcast data have also been applied to harbour design and underkeel clearance applications, which have received peer-review by international experts.

---

[1] From NCDC, NOAA, Zhang (2006).

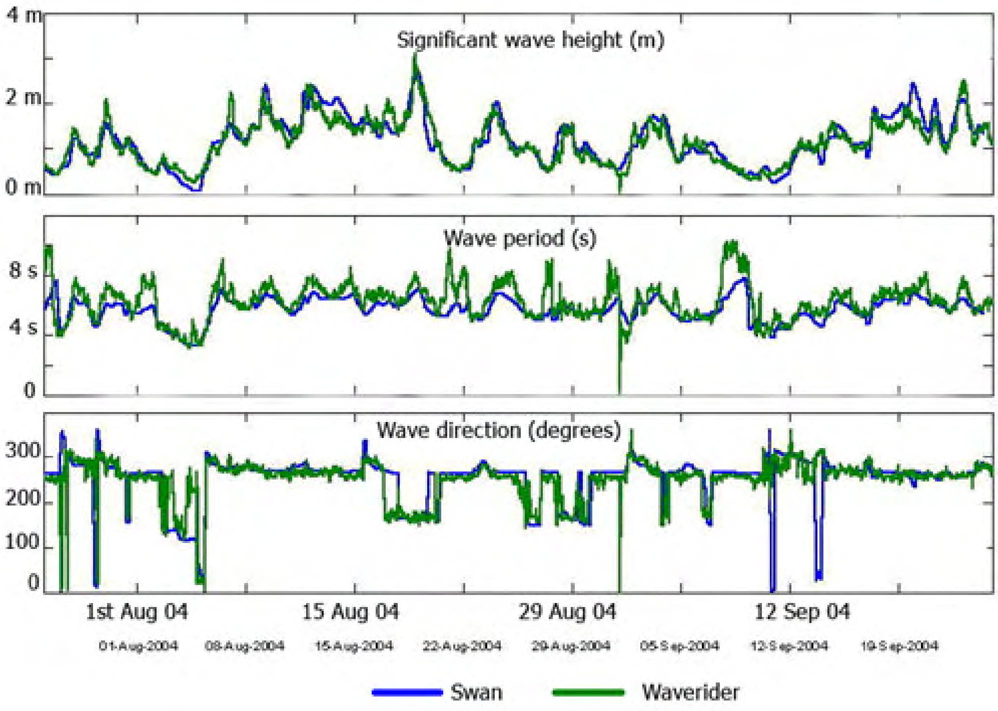


Figure 2.4 Validation time-series comparing the MSL wave hindcast with waverider buoy data collected at the Kupe Gas Field (35 km south of Hawera). See Figure 3.1 for location.

2.2.5 Spectral parameters

Directional wave spectra were output at hourly intervals over the hindcast run, and 10 years of data were available for the present study (1998 – 2007). The standard spectral wave parameters were derived as follows.

Given a directional wave spectrum $S(f,\theta)$, the 1-dimensional spectrum is obtained by integrating over directions:

$$S(f) = \int_0^{2\pi} S(f,\theta)d\theta \qquad (2.1)$$

From the computed spectral energy density $S(f)$, the peak frequency f_p and peak energy $S_p = S(f_p)$ of the spectrum are located. Spectral moments

$$M_j = \int_0^\infty f^j S(f)\, df \qquad (2.2)$$

are computed, allowing further statistics to be defined:

significant height $H_s = 4\sqrt{M_0}$ (2.3)

mean period $T_{m1} = M_0 / M_1$ (2.4)

mean apparent period $T_{m2} = \sqrt{M_0 / M_2}$ (2.5)

mean frequency $f_{mean} = M_1 / M_0$ (2.6)

mean crest period $T_{cr} = \sqrt{M_2 / M_4}$ (2.7)

spectral width $SW = 1 - \frac{{M_2}^2}{M_0 M_4}$ (2.8)

T$_{m2}$ is often used as a spectral approximation of the zero-down-crossing period statistic *Tz*.

Directional moments are:

$$M_c = \int_0^\infty \int_0^{2\pi} S(f,\theta) \cos\theta \, d\theta\, df \qquad (2.9)$$

$$M_s = \int_0^\infty \int_0^{2\pi} S(f,\theta) \sin\theta \, d\theta\, df \qquad (2.10)$$

The mean direction is $\theta_0 = \arctan\left(\frac{M_s}{M_c}\right)$ (2.11)

and the directional spread is $\Delta = \sqrt{2 - \frac{2\sqrt{M_c^2 + M_s^2}}{M_0}}$. (2.12)

The spectral peakedness parameter (Goda, 1970) is given by

$$Q_p = \frac{2}{{M_0}^2} \int_0^\infty f\, S(f)^2\, df\,. \tag{2.13}$$

2.3 Tidal current modelling

The MSL implementation of POM (Princeton Ocean Model) was used to hindcast the tidal currents in the New Zealand region. POM is a primitive equation ocean model that numerically solves for oceanic current motions. The details of model implementation are described in Mellor (2004)[2]. POM has been used for numerous scientific applications studying oceanic and shelf circulation.

2.3.1 Current Model

For the tidal simulations, POM was used in a vertically integrated two-dimensional mode, solving the momentum and mass conservation equations given by:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -g\frac{\partial \eta}{\partial x} - \frac{1}{\rho}\frac{\partial P_a}{\partial x} + A_H\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{\tau_w^x}{\rho h} - \frac{\tau_b^x}{\rho h}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} - fv = -g\frac{\partial \eta}{\partial y} - \frac{1}{\rho}\frac{\partial P_a}{\partial y} + A_H\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{\tau_w^y}{\rho h} - \frac{\tau_b^y}{\rho h}$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial (u[h+\eta])}{\partial x} + \frac{\partial (v[h+\eta])}{\partial y} = 0 \tag{2.14 a,b,c}$$

where t is the time, u and v are the depth-averaged velocities in the x and y directions respectively, h the MSL depth, η is the elevation of the surface, g the gravitational acceleration, f the Coriolis parameter, ρ the density of water, and P_a is atmospheric pressure. A_H is a horizontal eddy viscosity coefficient, calculated with a Smagorinsky parameterisation,

$$A_H = C_m \Delta x \Delta y \frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right]^{\frac{1}{2}} \tag{2.15}$$

---

[2] The numerical model code is freely available as open source code.

with C_m set at 0.2.

The surface and bottom shear stress, τ_w and τ_b are due to wind and bottom friction. The bed shear stress is parameterised with a quadratic type friction law,

$$\tau_b^x = C_D\sqrt{\left(u^2+v^2\right)}u \quad \tau_b^y = C_D\sqrt{\left(u^2+v^2\right)}v \qquad (2.16\text{ a,b})$$

that depends on an adjustable drag coefficient, $C_D \sim 10^{-3}$. Surface shear stresses are set to zero for the tidal simulations.

The model equations are solved with finite differences and explicit time-stepping, limited by a Courant condition. A time step of 8 s was used for the regional grid, and a time step of 5 s for the nested fine-scale grid.

2.3.2 Boundary conditions

The same boundary conditions are applied at all open boundaries. For the surface elevation, an Orlanski (1976) type radiation boundary condition is applied, but with the normal component of the outgoing phase speed determined as the normal projection of the full oblique phase speed. (*NPO* in Marchesiello *et al.,* 2001). For the normal component of depth-averaged velocity, u_n, a Flather (1976) type constraint is used,

$$u_n = u_n^b + \sqrt{\frac{g}{h}}\left(\eta - \eta^b\right) \qquad (2.17)$$

The boundary values of u_n^b and η^b are known boundary values for the surface elevation and depth-averaged current.

The TPXO7.0 global inverse tidal solution (Egbert and Erofeeva, 2002) was used to prescribe the tidal elevation and current velocity around the coarse grid. Elevations and velocities from the coarse domain solution were then used for the boundaries of the fine scale grid.

2.3.3 Model output

The 2D hydrodynamic model was run for a period of 40 days and then post-processed to derive the primary nine tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4) for each node in the domain. The modelled open ocean tidal flows have been validated at several sites in the offshore Taranaki region as part of the engineering design studies for oil and gas projects. The constituents of tidal elevation within the regional and high-resolution domains (i.e. Cook Strait and Foveaux Strait) were also validated against the published tidal constituents for discrete locations.

3 WAVE ENERGY DEFINITIONS AND CONVERSIONS

3.1 Energy of the wave field

The total wave energy (E_t) is given by;

$$E_t = E_p + E_k = \frac{1}{8}\rho g H^2 \tag{3.1}$$

Where ρ is the density of seawater (~1025 kg.m^{-3}), g is the acceleration due to gravity (9.81 m.s^{-1}) and H is the wave height.

The total wave energy (eqn. 3.1) is the energy per unit wave crest length, averaged over the wavelength. An alternative energy estimate omits the *1/L* term (Komar, 1976), and is found by multiplying E_t by the wavelength (L) to define *EL*. According to linear theory,

$$L = \frac{gT^2}{2\pi}\tanh(kh) \tag{3.2}$$

where T is the wave period, h is the water depth and k is the water wave number.

3.2 Wave energy flux

The energy flux (measured in watts per unit of wave crest, W.m^{-1}), is the rate at which energy is being transmitted, and represents the power of the wave field. The energy flux (P) is the average energy in the wave multiplied by the rate at which that energy is propagating (i.e. the group velocity, *Cg*).

$$P = E \times C_g \tag{3.3}$$

where

$$C_g = \frac{1}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right)C \tag{3.4}$$

and *C* is the wave celerity, given as

$$C = \frac{gT}{2\pi}\tanh(kh) \tag{3.5}$$

From a spectrum of potential wave energy (i.e. measured or modelled), the energy flux can be estimated through integration over the entire spectrum. However, a wave spectrum is not always available so an alternative parametric deep-water estimate (P_p) is often applied (Hagerman and Bedard, 2003);

$$P_p = 0.42 T_p H_s^{\,2} \tag{3.6}$$

where T_p is the peak spectral wave period. This parametric estimate of the available wave power (eqn. 3.6) provides a very similar result to the spectral integration method in deep water. The spectral integration method is used in this report to represent the available wave power for generation assessment.

The ability of a specific device to extract energy from a spectral sea state is typically reported by the developers as a ‘power matrix’. This matrix provides a power output for any combination of the wave height - wave period estimates. Typically, the significant wave height (H_s) is used along with the wave energy period (T_e), where in deep water.

$$T_e = \frac{m_{-1}}{m_0} \tag{3.7}$$

In intermediate depths it is important to take account of the effect of depth on wave group velocity. The most appropriate way to consider energy period is from the conceptual definition as the period of the regular wave that has “the same parametric height and the same power density as the sea-state under consideration”. If the total power density and the parametric wave height (H_s) are already known, this leads to,

$$T_e = \frac{64\pi}{\rho g^2} \cdot \frac{P}{H_{m0}^{\;2}} \tag{3.8}$$

Alternatively, Burger *et al* (2005) derived the energy period (T_e) based on the Bretschneider spectrum, where

$$T_e = 1.15.T_z \text{, or} \tag{3.9}$$

$$T_e = 0.86.T_p \tag{3.10}$$

where T_z is the zero down-crossing wave period and T_p is the peak wave period.

It is worth noting that the definitions and equations for wave power are depth-integrated, and provide a measure of total power that might be extracted by a perfect device. However in reality a wave device usual operates at the surface or in a discrete part of the whole water column, and could not recover all of the available power.

3.3 Wave power devices

There are various types of possible wave power devices, including the point absorber; surfacing following or attenuator; terminator (perpendicular to wave propagation); oscillating water column; and overtopping device. Within this range of devices, the power take-off mechanisms include: hydraulic ram, elastomeric hose pump, pump-to-shore, hydroelectric turbine, air turbine, and linear electrical generator.

The available power matrix data released by developers are typically derived from tank testing or numerical modelling (or a combination of both), but to date few (if any) have been validated with full-scale tests. The sea-states referred to by the height and period parameters are therefore usually two-parameter idealised models (such as the Bretschneider spectrum) combined with a simple directional spreading function.

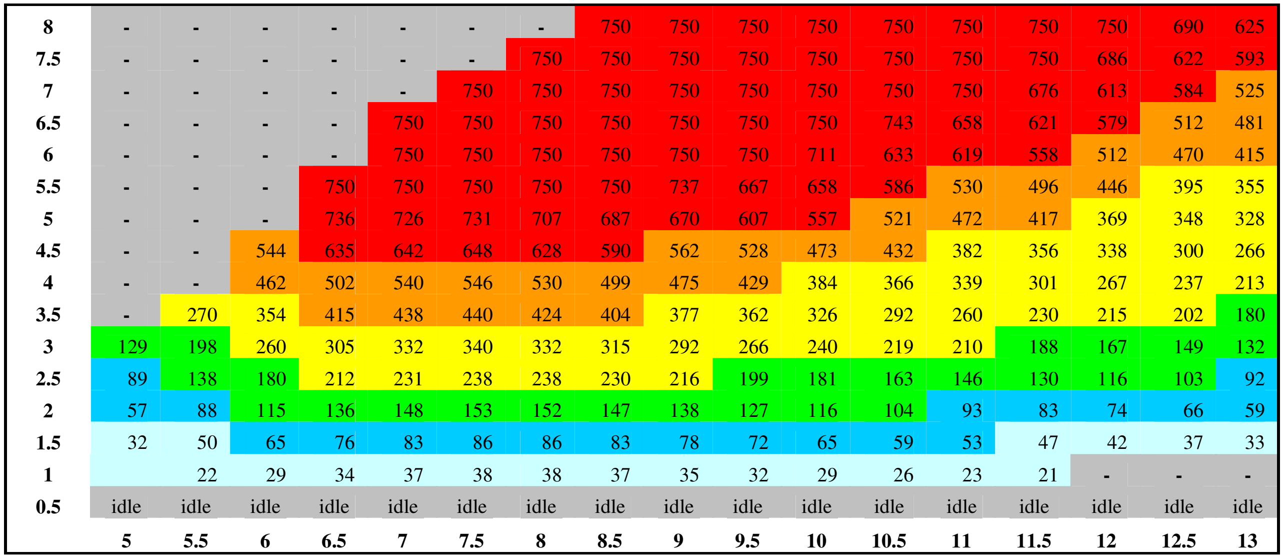
This report examines the possible power recoverable for three different wave energy devices, based on their published power matrices;

- **750 kW Pelamis device.** This device has 4 segments and 3 power modules and, for wave events with $T_e > 13$ s, the $T_e = 13$ s power curve has been applied. The power matrix is provided in Table 3.1, based on a significant wave height and peak spectral wave periods.

- **Hypothetical modified 1500 kW Pelamis device.** The University of Edinburgh (2006) scaled up the Pelamis power matrix to represent anticipated future machines. This matrix (Table 3.2) assumes a device 180 m in length, with 5 segments and 4 power modules, suitable for water depths ranging from 50-150 m. For wave events with $T_e > 19$ s, the $T_e = 19$ s power curve has been applied, while for events with $H > 3$ m, the $H = 3$ m power curve has been applied. RMS wave height is used in this matrix.

- **Hypothetical 750 kW Single Point Absorber (SPA).** This device has the performance characteristics described in Table 3.3, and specification listed in Table 3.4. For wave events with $T_e > 19$ s the $T_e = 19$ s power curve has been applied, while for events with $H > 3$ m the $H = 3$ m power curve has been applied. RMS wave height is used in this matrix.

Table 3.1 The 750 kW Pelamis power matrix (http://www.pelamiswave.com/media/power-matrix.jpg). Values are in kW.



Sig. wave height (m)	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13
8	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
7	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
6	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
5	-	-	-	736	726	731	707	687	670	607	557	521	472	417	369	348	328
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
4	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
3	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
2	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
1		22	29	34	37	38	38	37	35	32	29	26	23	21	-	-	-
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle

Wave energy period (s)

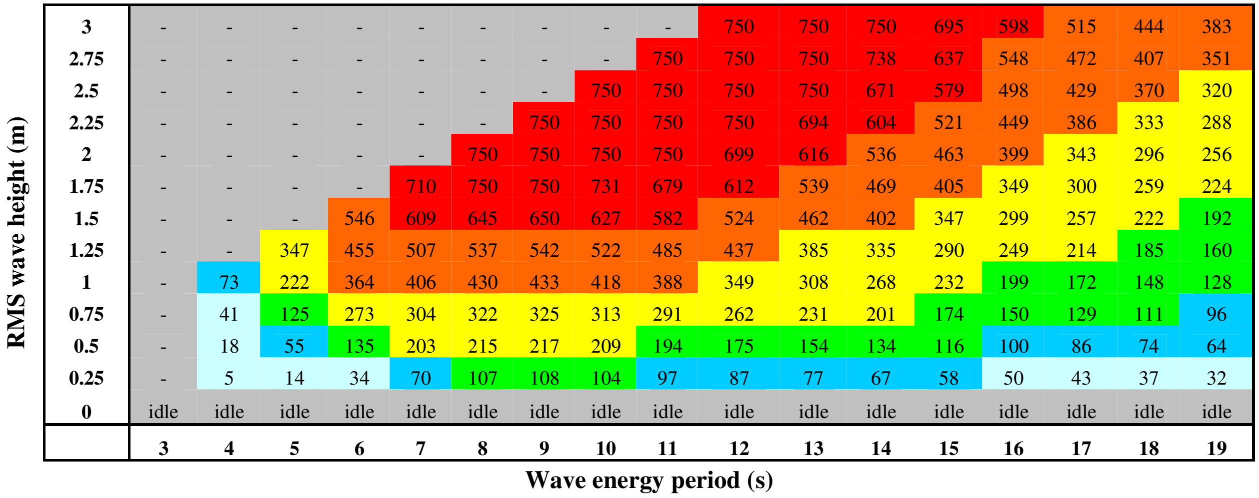
Table 3.2 Hypothetical 1500 kW Pelamis power matrix. Values are in kW.

RMS wave height (m)

3	-	-	-	-	-	-	-	-	-	1500	1500	1500	1500	-	-	-	-
2.75	-	-	-	-	-	-	-	-	1500	1500	1500	1500	1500	1453	-	-	-
2.5	-	-	-	-	-	-	-	1500	1500	1500	1500	1500	1470	1319	1192	-	-
2.25	-	-	-	-	-	-	1500	1500	1500	1500	1500	1450	1350	1175	1039	900	-
2	-	-	-	-	-	1500	1500	1500	1500	1500	1450	1320	1180	1008	865	750	635
1.75	-	-	-	-	1500	1500	1500	1500	1500	1440	1277	1119	971	845	724	607	490
1.5	-	-	-	1450	1500	1500	1500	1460	1444	1253	1071	915	782	651	540	450	361
1.25	-	-	650	1258	1470	1450	1467	1299	1136	968	826	688	567	462	378	314	251
1	-	95	427	871	1116	1170	1106	969	834	688	558	449	366	297	242	201	161
0.75	-	53	241	525	730	769	709	605	493	397	317	254	206	168	137	114	91
0.5	-	24	108	237	336	358	326	274	222	178	142	114	93	75	61	51	41
0.25	-	5	27	62	88	94	85	72	58	47	33	22	18	14	10	5	0
0	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**

Wave energy period (s)

Table 3.3 Hypothetical 750 kW SPA power matrix. Values are in kW.



RMS wave height (m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
3	-	-	-	-	-	-	-	-	-	750	750	750	695	598	515	444	383
2.75	-	-	-	-	-	-	-	-	750	750	750	738	637	548	472	407	351
2.5	-	-	-	-	-	-	-	750	750	750	750	671	579	498	429	370	320
2.25	-	-	-	-	-	-	750	750	750	750	694	604	521	449	386	333	288
2	-	-	-	-	-	750	750	750	750	699	616	536	463	399	343	296	256
1.75	-	-	-	-	710	750	750	731	679	612	539	469	405	349	300	259	224
1.5	-	-	-	546	609	645	650	627	582	524	462	402	347	299	257	222	192
1.25	-	-	347	455	507	537	542	522	485	437	385	335	290	249	214	185	160
1	-	73	222	364	406	430	433	418	388	349	308	268	232	199	172	148	128
0.75	-	41	125	273	304	322	325	313	291	262	231	201	174	150	129	111	96
0.5	-	18	55	135	203	215	217	209	194	175	154	134	116	100	86	74	64
0.25	-	5	14	34	70	107	108	104	97	87	77	67	58	50	43	37	32
0	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle

Wave energy period (s)

Table 3.4 Hypothetical 750 kW Single Point Absorber wave energy converter characteristics

Natural Period (s)	11
Damping Coefficient	0.06
Efficiency (%)	80
Rating (kW)	750
Radius (m)	6
Stroke (m)	3

3.4 Wave model validation for wave power

The MSL numerical wave hindcast model has been rigorously validated against measured wave data from around New Zealand, at nearshore and offshore (continental shelf) locations. However, the relationship between wave height and wave power is non-linear, which means that small errors in the hindcast wave heights can lead to very significant errors in the mean wave power assessment for a location. Also, the spatial and temporal scale used in the numerical hindcasting process is important so that topographic and bathymetric effects on the waves' physics can be properly resolved. The scale factor may be important when comparing the high-resolution outputs from the MSL model with other wave hindcast results that have employed a coarser-scale domain.

For the present assessment, a further regional validation process has been undertaken specifically for the derived wave power values. This exercise has been undertaken using waverider buoy data from six locations around New Zealand, as shown on Figure 3.1. For this validation analysis, the deepwater parametric method (eqn. 3.6) was used to estimate the wave power flux from both the measured and modelled wave data. This method was used because wave spectra were not available from all the buoy sites.

The validation results (Table 3.5) clearly show that the wave model is accurately representing the average energy flux for the wide range of locations tested. The modelled results are all within 20% of the measured power values, and there are no indications of systematic under-prediction or over-prediction throughout the range of environments tested. This is a very robust validation, particularly considering the use of a parametric technique that assumes a generic spectral shape.

A further validation was undertaken using the full wave spectral integration method, using measured wave spectra from the offshore Maari Field in August - September 2003. During this period, the mean measured spectral wave power was 34.8 kW.m^{-1}, while the hindcast spectral wave power for the same period was 38.8 kW.m^{-1}.

One of the most energetic coastal locations in New Zealand is the Southland region. During 1989, Electricorp Production commissioned a wave energy assessment involving wave data collection in 90 m water depth in the Western Foveaux Strait (46.52083 S, 167.45833 E). Over the Autumn months of March-May 1989, the averaged measured spectral wave power was 65.4 kW m^{-1} and the mean significant wave height was 3.66 m (BTW, 1989). By comparison, the mean spectral power from the MSL hindcast model for this same location during all the March-May periods over 1998-2007 was 73.7 kWm^{-1} and the mean significant wave height was 3.55 m.

In summary, the hindcast techniques that have been applied in this assessment have received due scrutiny by international experts, and MSL hindcast wave data have been used extensively for the engineering design criteria within New Zealand’s’ offshore oil industry. Further, the site-specific validations for wave power clearly show that the MSL hindcast method provides a reliable representation of the wave energy resource.

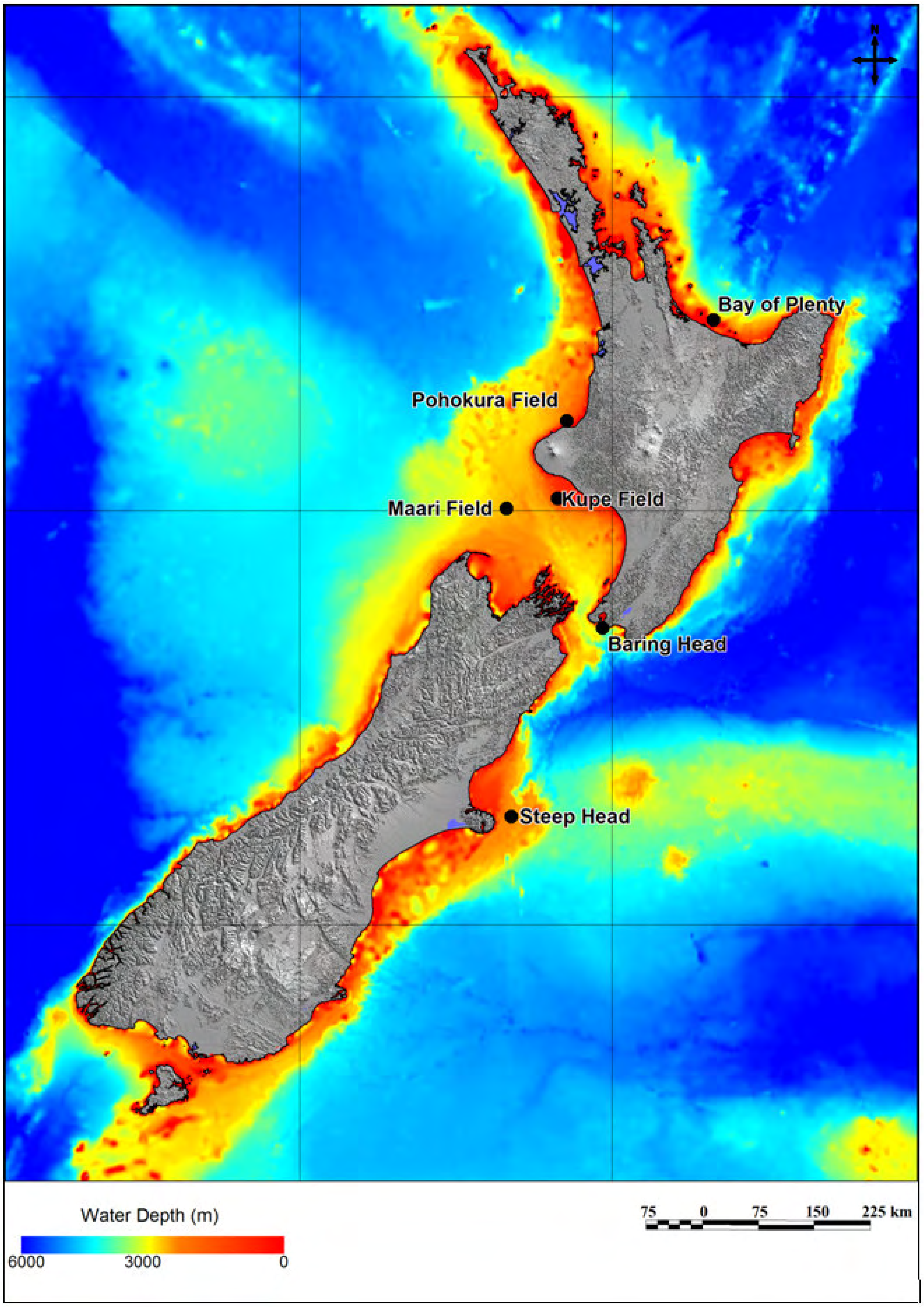


Figure 3.1 Location of the wave power validation sites

Table 3.5 Wave hindcast validation results

Data location	Data source	Duration		Mean Hs (m)	Mean Hs^2 (m^2)	Mean wave power (W m^{-1})
Kupe Field	MetOcean	Apr-Nov 2007	Measured	2.02	5.05	21281
			Modelled	2.02	4.88	22448
Maari Field	MetOcean	Sept-Dec 2007	Measured	2.23	6.2	27106
			Modelled	2.19	5.67	27213
Pohokura Field	MetOcean	Jun-Nov 2003	Measured	1.78	3.99	18039
			Modelled	1.94	4.38	20690
Baring Head	NIWA/GWRC	Jan-Dec 2007	Measured	1.26	2.13	9060
			Modelled	1.16	1.88	8380
Steep Head	NIWA/ECAN	Jan-Dec 2007	Measured	2.01	4.69	21847
			Modelled	1.74	3.71	17468
Steep Head	NIWA/ECAN	Mar-Dec 2003	Measured	1.99	6.20	19442
			Modelled	1.88	4.11	18900
Bay of Plenty	EBOP	Jun-Dec 2004	Measured	0.99	1.36	5094
			Modelled	1.14	1.81	5647

4 TIDAL STREAM ENERGY DEFINITIONS AND CONVERSIONS

4.1 Tidal flow energy

The instantaneous power density (*P*) of a flowing fluid incident to an underwater turbine is given as;

$$\left(\frac{P}{A}\right)_{Water} = \frac{1}{2}\rho U^3 \tag{4.1}$$

where *A* is the cross-sectional area of flow intercepted by the device (i.e. the area swept by the turbine rotor, m^2) and ρ is the density of water (~1025 $kg.m^{-3}$ for seawater) and *U* is the current speed ($m.s^{-1}$). Because the power density varies with the cube of the current velocity (eqn. 4.1), it increases rapidly with current speed (i.e. Fig. 4.1).

Power densities of 500 - 1000 $W.m^{-2}$ are available for flow velocities of between 1-1.3 $m.s^{-1}$ (2-2.5 knots). In order to determine the power density distribution for a particular site it is necessary to identify the velocity distribution and convert the velocity distribution into a power density distribution; from which various descriptive statistics can be derived (i.e. mean, median and percentiles of the power density distribution).

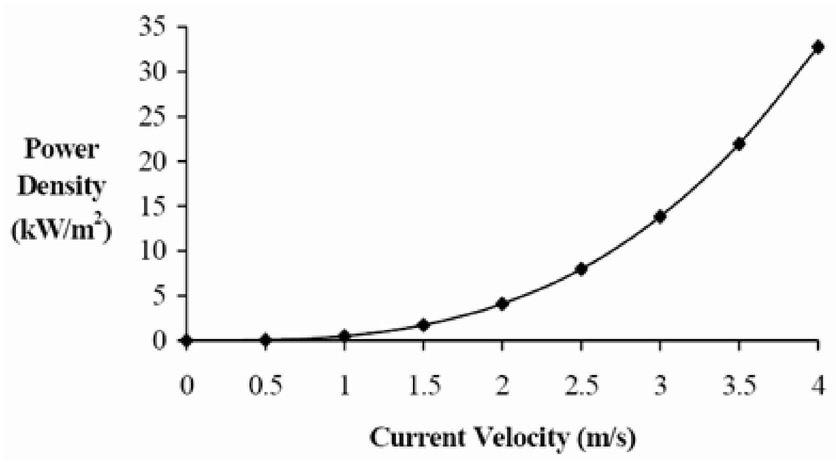


Figure 4.1 Incident power density as a function of current velocity

4.2 Tidal stream devices

There are two main categories of tidal devices; tidal barrages and tidal current turbines. Barrages are not open-coast devices and are not considered further in this report.

Tidal stream devices operate using the same principle as wind turbines; generating power directly from the water current, typically where the flows exceed 0.5 $m.s^{-1}$. The turbines can be orientated either horizontally or vertically and the systems can be either floating or secured directly to the seabed.

The recoverable tidal flow energy is limited by the characteristics of the site (i.e. water depth etc) as well as environmental considerations (i.e. the impact of a device on the circulation patterns). Typically the usable cross-sectional area available is limited at the top and bottom of the profile in order to facilitate navigational clearance requirements; eliminating the upper 15-20 m in water channels maintained for ocean-going vessels and 5 m elsewhere in order to provide clearance for shallow-draft vessels. At the bottom the turbine should be above the low-speed benthic boundary layer, which is approximately $^{1}/_{10}$ of the low water depth (~MLWS). The maximum energy that can be extracted is calculated from the power density multiplied by the usable cross-sectional area between the top and bottom limits as described above.

4.3 Power recovery efficiency

The power recovery efficiency and turbine performance can be estimated by considering the power conversion efficiency of each step of the extraction process, beginning with the power of the flowing water stream and proceeding through the turbine, drive train, generator and power conditions steps.

Turbine efficiency varies with the velocity of water flow. A plot of a turbines output as a function of flow speed typically consists of three regions; i) zero to cut-in speed, ii) cut-in speed to rated speed, and iii) greater than rated speed (Fig. 4.2)

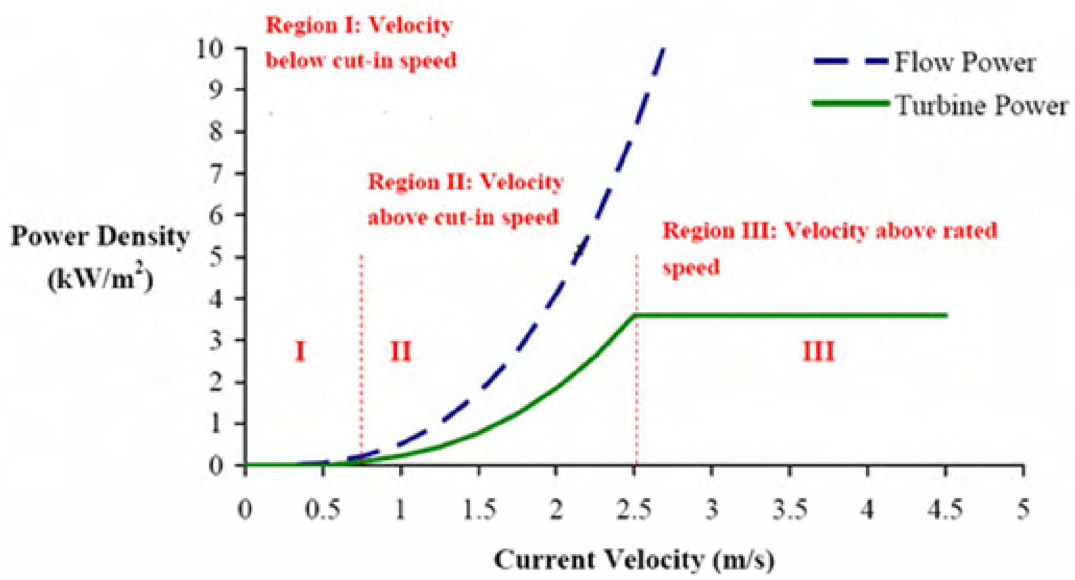


Figure 4.2 Typical plot of turbine output power versus flow speed

In Region I, velocities are below the cut-in speed and the turbines' blades do not create sufficient lift to rotate the drive train so no power is generated. In Region III when velocities exceed the rated speed of the turbine, power output is held constant, typically at the turbine's rated power, regardless of the velocity. Rated power output is maintained by either applying a force to the rotor shaft or changing the pitch angle of the turbine blades to generate less lift. In Region II (between the cut-in speed and the rated speed) the turbine's output depends on a chain of conversion efficiencies, including the turbines power coefficient (C_p) and the power take-off efficiency (η), such that;

$$P_{electric} = \overline{P} \times C_p \times \eta \qquad (4.2)$$

where $\overline{P}$ is the power density of the water passing through the area swept by the turbine, i.e.

$$\overline{P} = \frac{1}{2}\rho U^3 A \qquad (4.3)$$

Where A is the area swept by the turbine rotor.

The power coefficient (C_p) is the ratio of the actual power produced to the kinetic energy of a stream tube the same diameter as the rotor, and is given as;

$$C_{p.} = \frac{P_{rotor}}{\frac{\pi}{8}\rho D^2 U^3} \qquad (4.4)$$

where D is the rotor diameter. During its field trials, the 11 m diameter single turbine *Seaflow* tidal energy device had instantaneous C_p values ranging from 0.2-0.6. When averaged, the values ranged between 0.38-0.45 depending on the current velocities. This appears to be fairly standard for tidal energy devices. The power take-off efficiency (η) is a function of the drive-train, generator and power conditioning of the unit, such that,

$$\eta = \eta_{dirve-train} \times \eta_{generator} \times \eta_{power\_conditioning} \qquad (4.5)$$

C_p **The power coefficient** - This is the efficiency with which the turbine extracts kinetic energy from the incoming flow. For water flowing through an unshrouded turbine, maximum extraction efficiency occurs when the flow speed at the rotor face is reduced by 1/3 relative to the free-stream velocity, which yields an optimal extraction efficiency of 16/27(~59%, i.e. the Lanchester-Betz limit). Shrouded devices can achieve higher efficiencies. Typical values of C_p for un-shrouded devices range from 0.2-0.6, and average out at around 0.45, or 45%.

$\eta_{drive-train}$ **The drive train efficiency.** This is the efficiency with which the energy extracted from the flow is delivered to the generator. Typical values range from 80-96%

$\eta_{generator}$ **The generator efficiency.** This is the efficiency with which the mechanical energy input to the generator is converted to electricity. Losses are primarily due to friction, and typical generator efficiency values range from 80-95%.

$\eta_{power\ conditioning}$ **The power conditioning efficiency.** This is the efficiency with which the electricity produced by the generator is conditioned to meet phase and voltage requirements of the local grid interconnection point. Losses are primarily electrical energy dissipated as heat, and typical power conditions efficiency values range from 90-98%.

For typical component efficiencies, the overall efficiency would be within the range of 40%, which is the proportion of incident flow power converted into properly conditioned electric power output.

4.4 Device specifics

For the purpose of this assessment, the time-series simulation of power generation has considered two generic devices; an unshrouded turbine with a diameter of 16 m, and an unshrouded turbine with a diameter of 10 m. The device specifics are listed in Table 4.1. Using these specifications, the generation of electrical power from the tidal stream was simulated in the time-domain at 15-minute intervals over a one-year period. The depth-average current speed was used directly for the simulation, rather than applying a current profile, which is a reasonable assumption given that the turbines used in this simulation occupy approximately the middle third of the water column. Site assessment results are provided in Section 7.

Table 4.1 Generic tidal device specifications

Parameter	Device 1	Device 2
Turbine diameter (m)	16	10
Cut-in speed ($m.s^{-1}$)	0.7	0.8
Rated speed ($m.s^{-1}$)	2.5	2.5
Power coefficient (C_p)	0.45	0.50
Drive-train efficiency	0.90	0.92
Generator efficiency	0.90	0.95
Power conditioning efficiency	0.95	0.95

5 WAVE ENERGY RESOURCE MAPS

A series of New Zealand-scale maps are presented to characterise the wave energy resources. These maps are derived from the MSL 10-year wave hindcast, and provide approximately 5 km spatial resolution.

The mean significant wave height is provided in Figure 5.1, showing a mean wave height gradient from the southwest of New Zealand to the northeast. The mean heights for an arbitrary sea fraction ($T<10s$) and swell fraction ($T>10s$) are presented in Figures 5.2 and 5.3, respectively. These maps are useful for characterising the mean sea state, and clearly show that the northeast sector of New Zealand is sheltered from the dominant Southern Ocean swells. Wave power is proportional to the square of the wave height, and for reference purposes the mean significant wave height squared is presented on Figure 5.4.

The maximum significant wave height over the period 1998-2007 is shown on Figure 5.5, providing an interesting pattern. While the mean wave energy is higher on the South and West coasts, some of the largest wave heights were observed on the East Coast of the North Island (from Wairapapa – East Cape). Isolated areas of high wave heights, for example around the Coromandel, are signatures of a single isolated storm event in the 10-year time-series.

Two figures that effectively characterise the New Zealand wave climate for potential generation are the mean wavelength of the equivalent energy period (Fig. 5.6) and the mean spectral wave power (Fig. 5.7). The mean wavelength plot shows the clear differences between the swell-dominated West Coast (with wavelengths around 150 m) and the sea-dominated East Coast (with wavelengths 50-100 m). The mean spectral wave power (Fig. 5.7) indicates that a mean annual resource of at least 30 $kW.m^{-1}$ is available within about 15 km of the shoreline along most of the West Coast of New Zealand, excepting the Western Cook Strait region and the North Taranaki Bight. The most energetic location for wave power is the Southland coast, from Fiordland to the west of Stewart Island. Along the East Coast of New Zealand, only the Catlins region in South Otago has an equivalent resource to the West Coast. In the North Island, the coastline from Wairarapa to East Cape is the next most energetic region, but with around one third of the median energy of the typical West Coast locations.

The mean power output from the three wave power conversion devices (discussed in Section 3.3) are presented in Figures 5.8 – 5.10. These data are derived from a 10-year time-series simulation (1998-2007) and represent the mean output from a single device, calculated for every node in the hindcast domain.

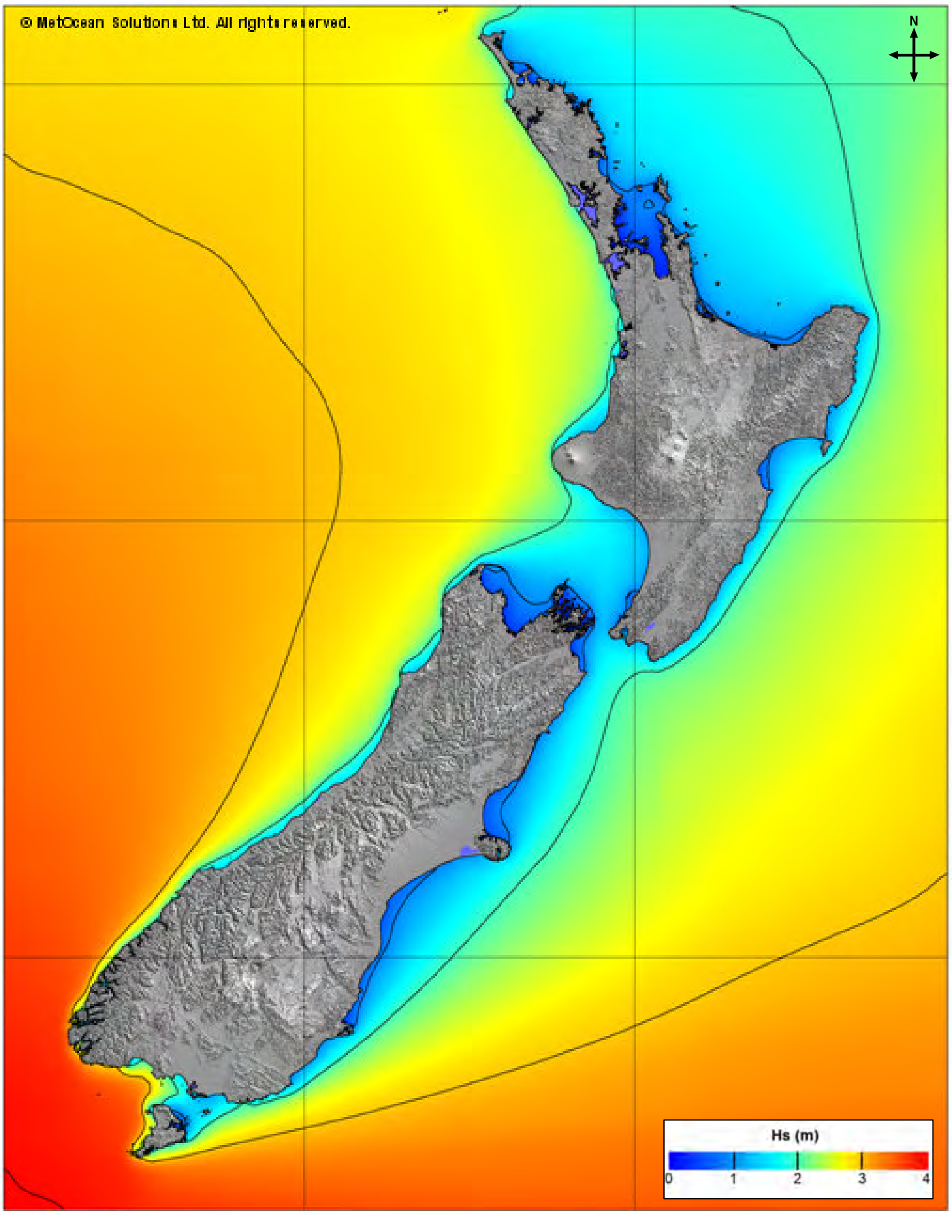


Figure 5.1 Mean significant wave height (1998-2007)

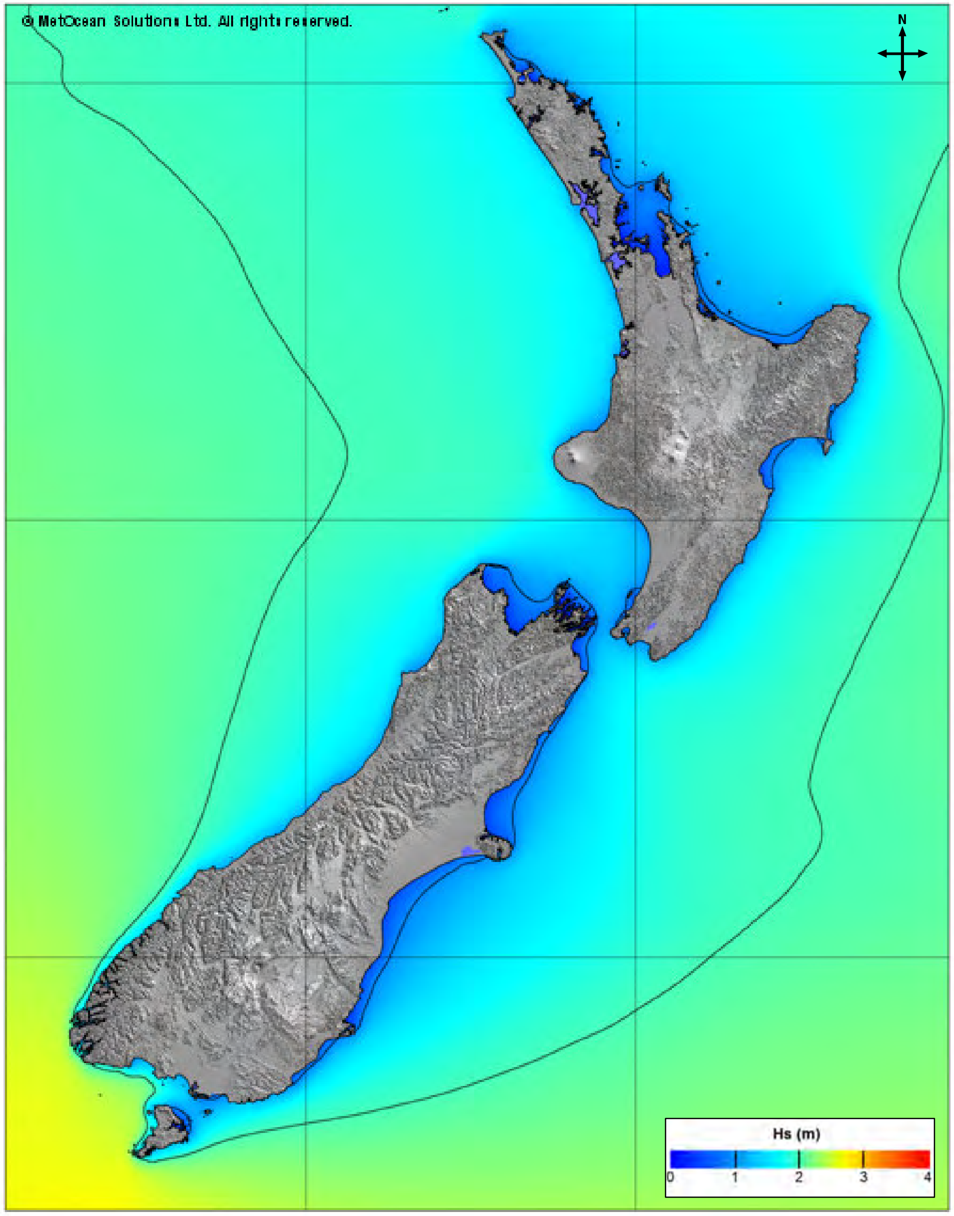


Figure 5.2 Mean significant sea wave (T<10s) height (1998-2007)

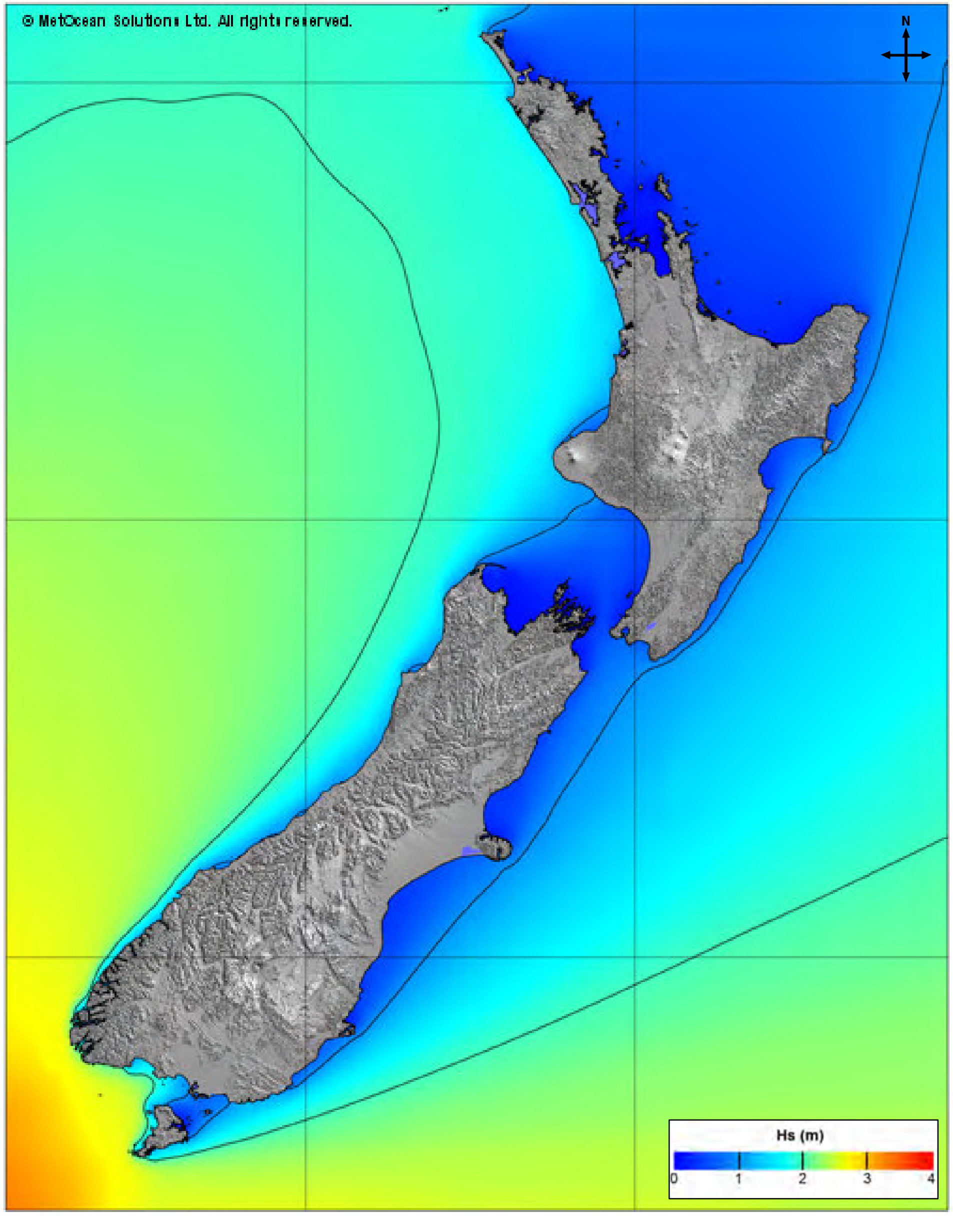


Figure 5.3 Mean significant swell wave (T>10s) height (1998-2007)

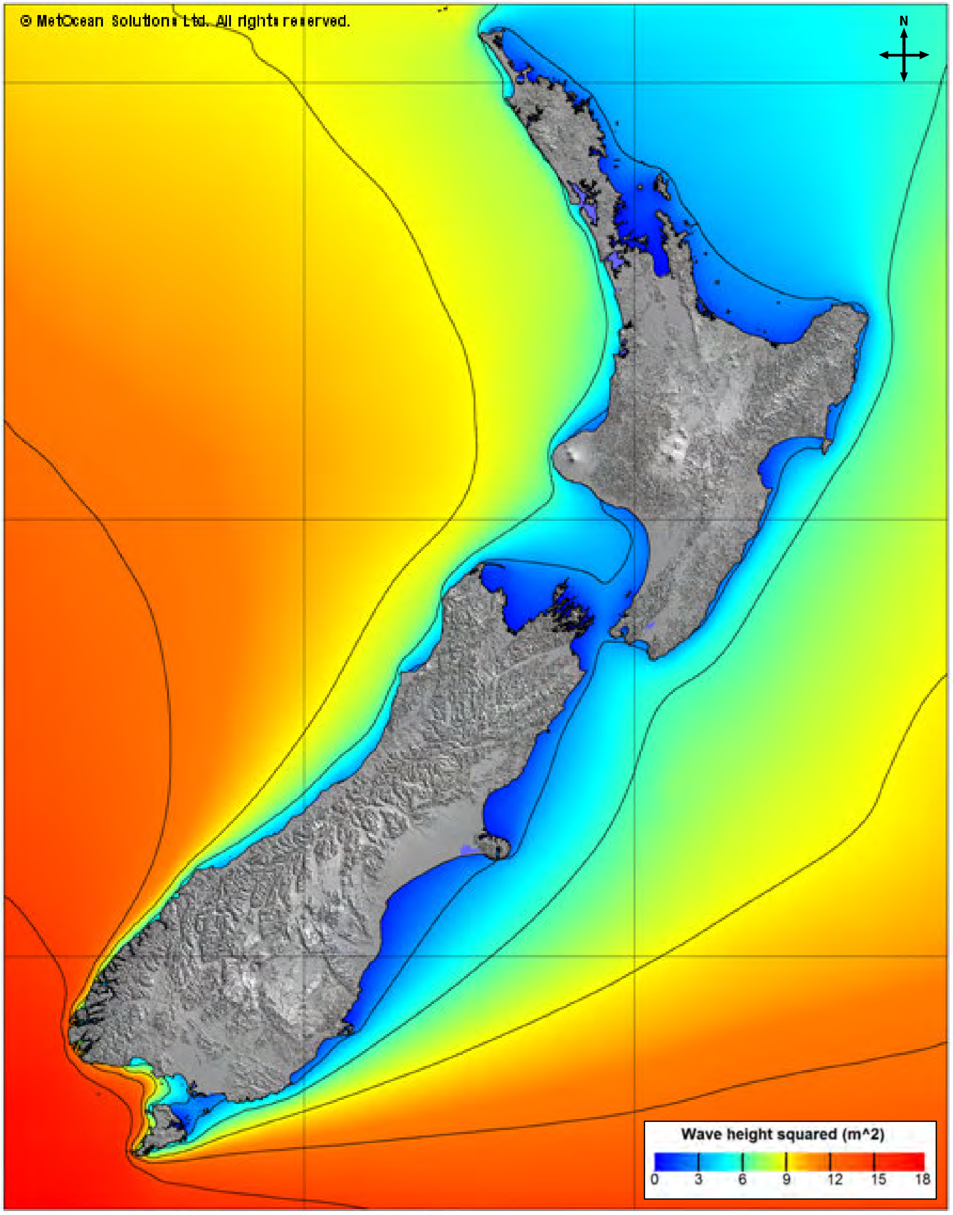


Figure 5.4 Mean significant wave height squared (1998-2007)

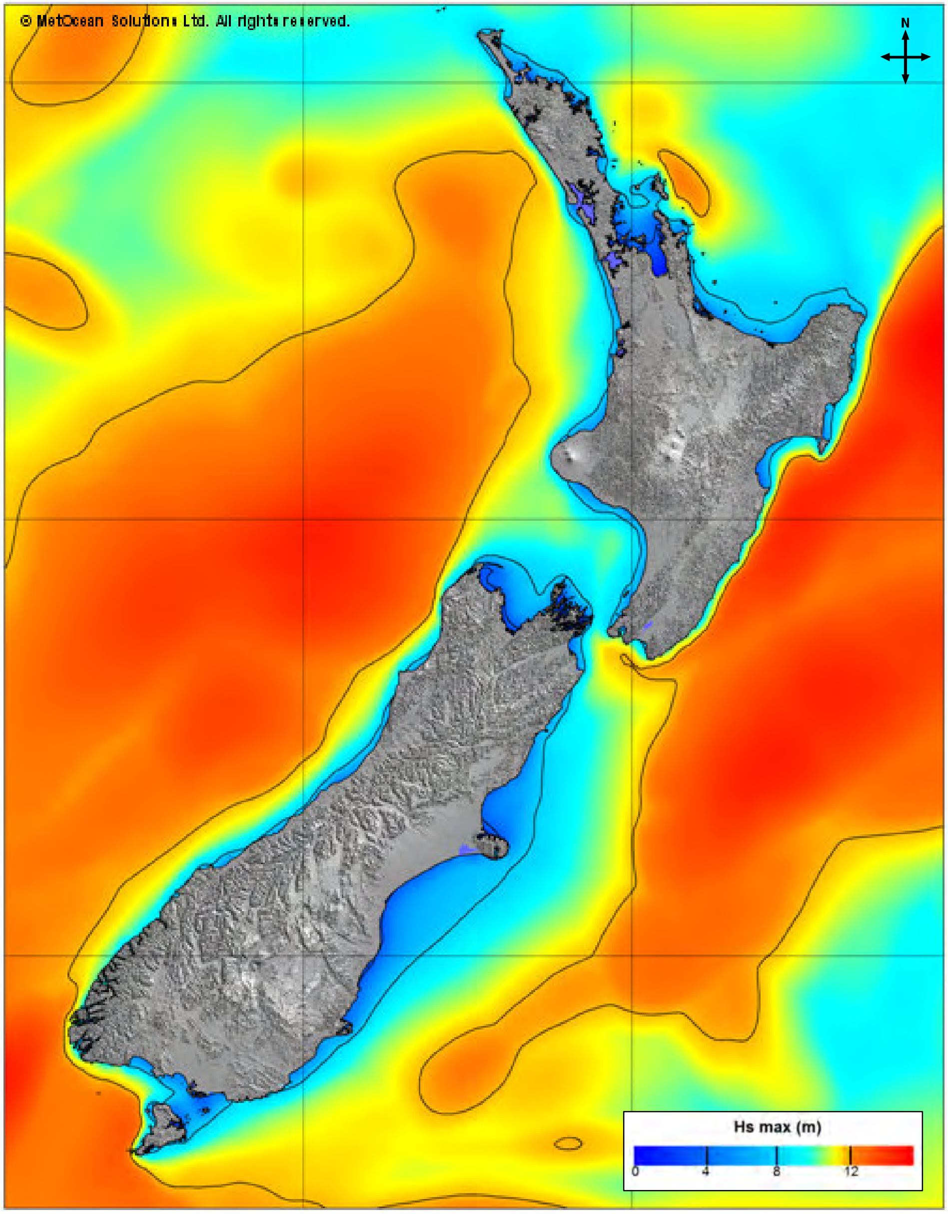


Figure 5.5 The maximum significant wave height hindcast over 1998-2007

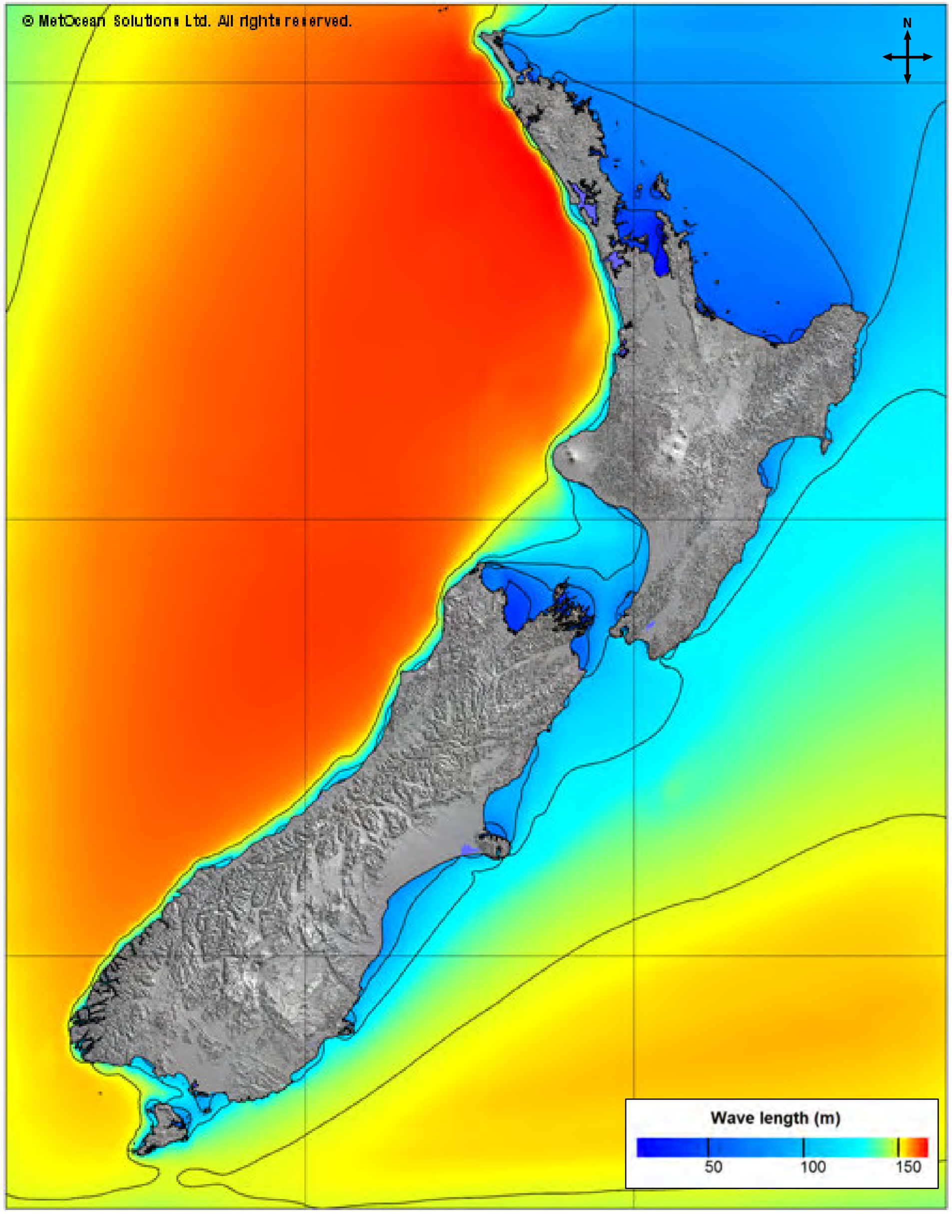


Figure 5.6 Mean wavelength (1998-2007)

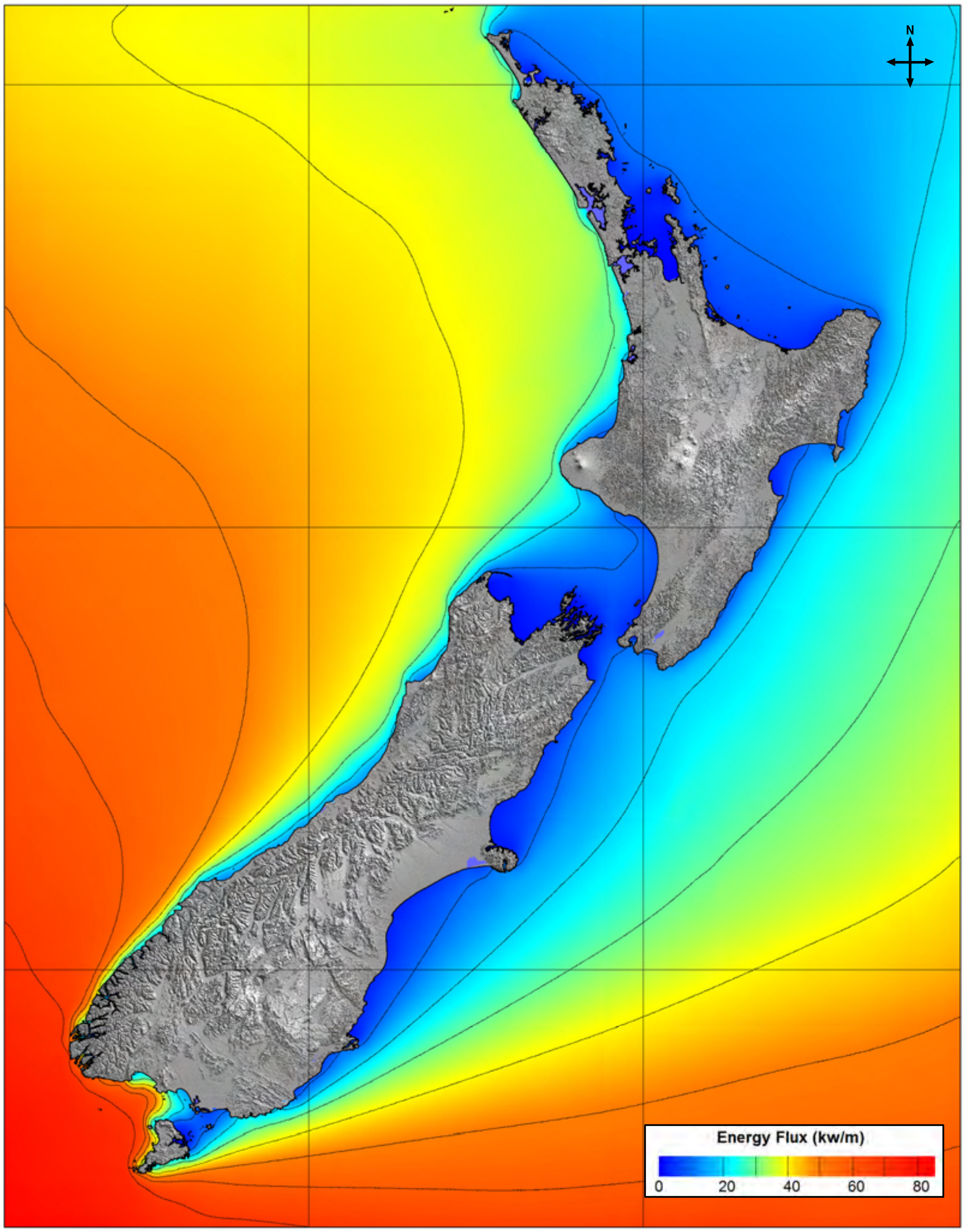


Figure 5.7 Mean spectral wave power (1998-2007)

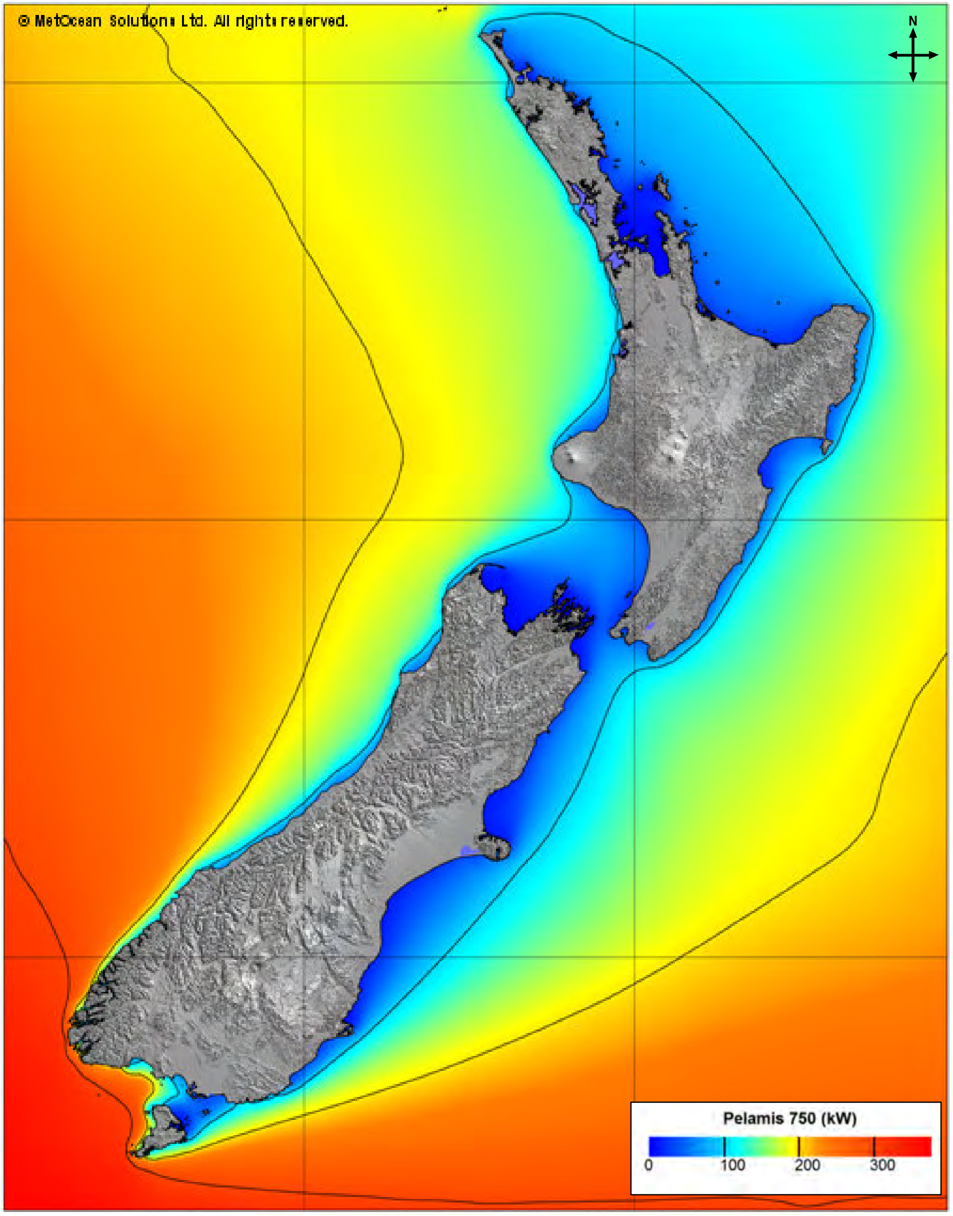


Figure 5.8 Mean power output from a single 750 kW Pelamis device (1998-2007)

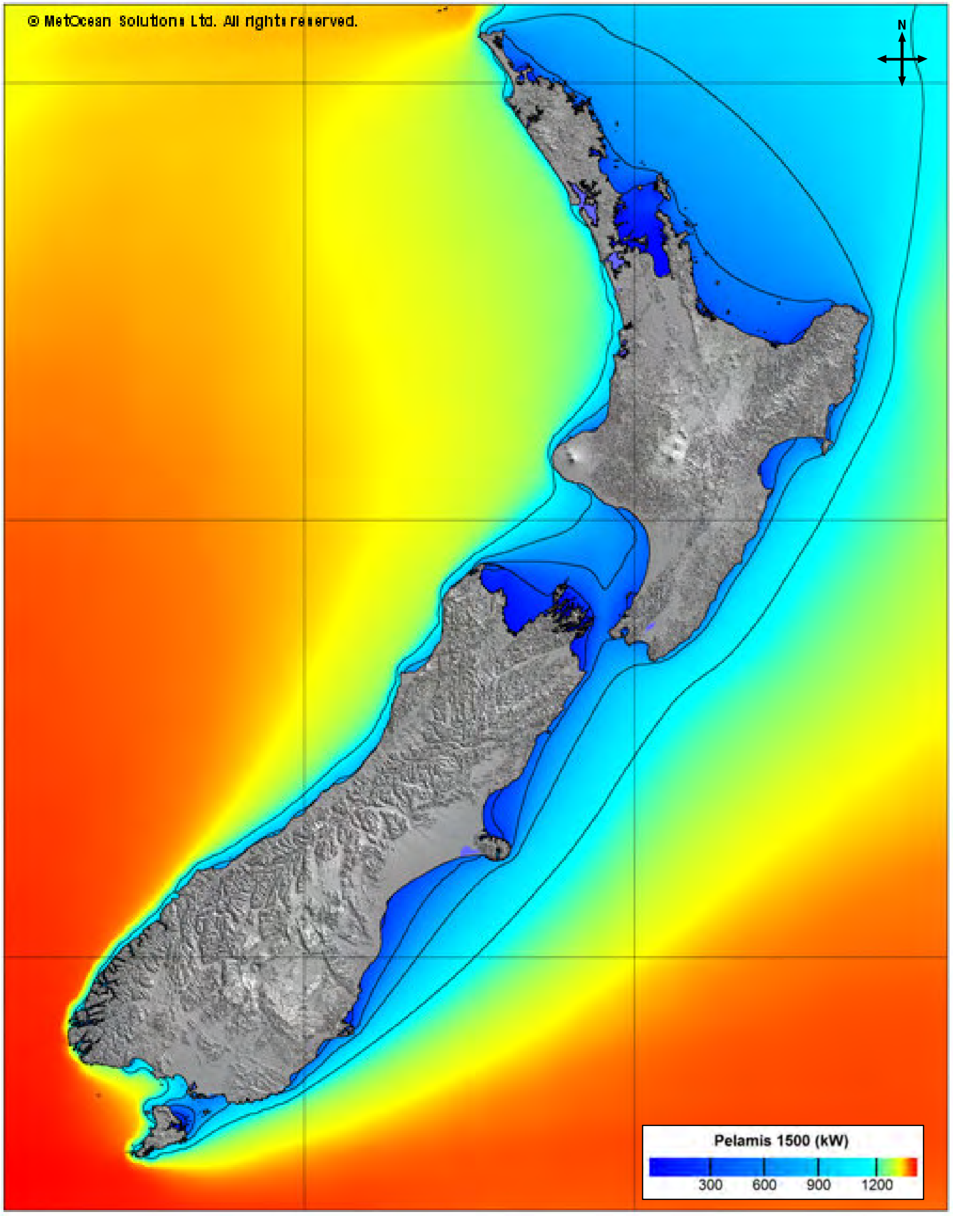


Figure 5.9 Mean power output from a single 1500 kW Pelamis device (1998-2007)

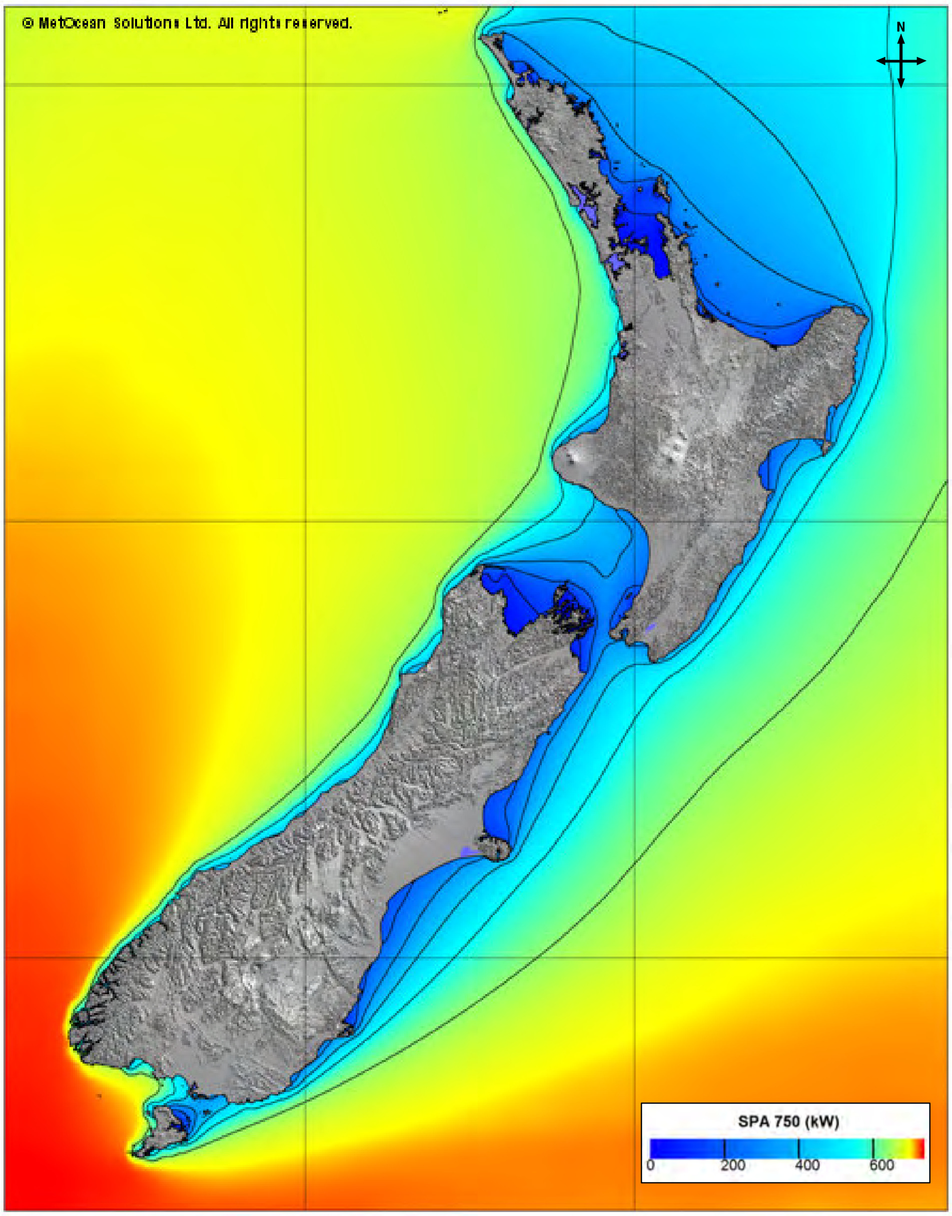


Figure 5.10 Mean power output from a single 750 kW SPA device (1998-2007)

6 WAVE ENERGY SITE ASSESSMENTS

6.1 Locations

Six coastal locations have been selected for detailed analysis of their wave power potential (Table 6.1; Fig. 6.1).) These locations have been chosen to represent a range of wave climates around New Zealand, within the realms of feasible grid connectivity. A common distance of 6 km offshore has been selected at each site, providing a range of water depths from 23-65 m. Wave and wave power statistics have been extracted for these locations from the MSL New Zealand regional wave hindcast simulation.

Table 6.1 Wave energy site assessment locations

Station	**Southland**	**Westport**	**Cape Egmont**	**Port Waikato**	**Gisborne**	**Wairarapa**
Depth (m)	31	65	51	23	39	62
Distance offshore (km)	6	6	6	6	6	6
Latitude	-46.401	-41.734	-39.287	-37.440	-38.708	-41.126
Longitude	167.677	171.390	173.682	174.635	178.148	176.137

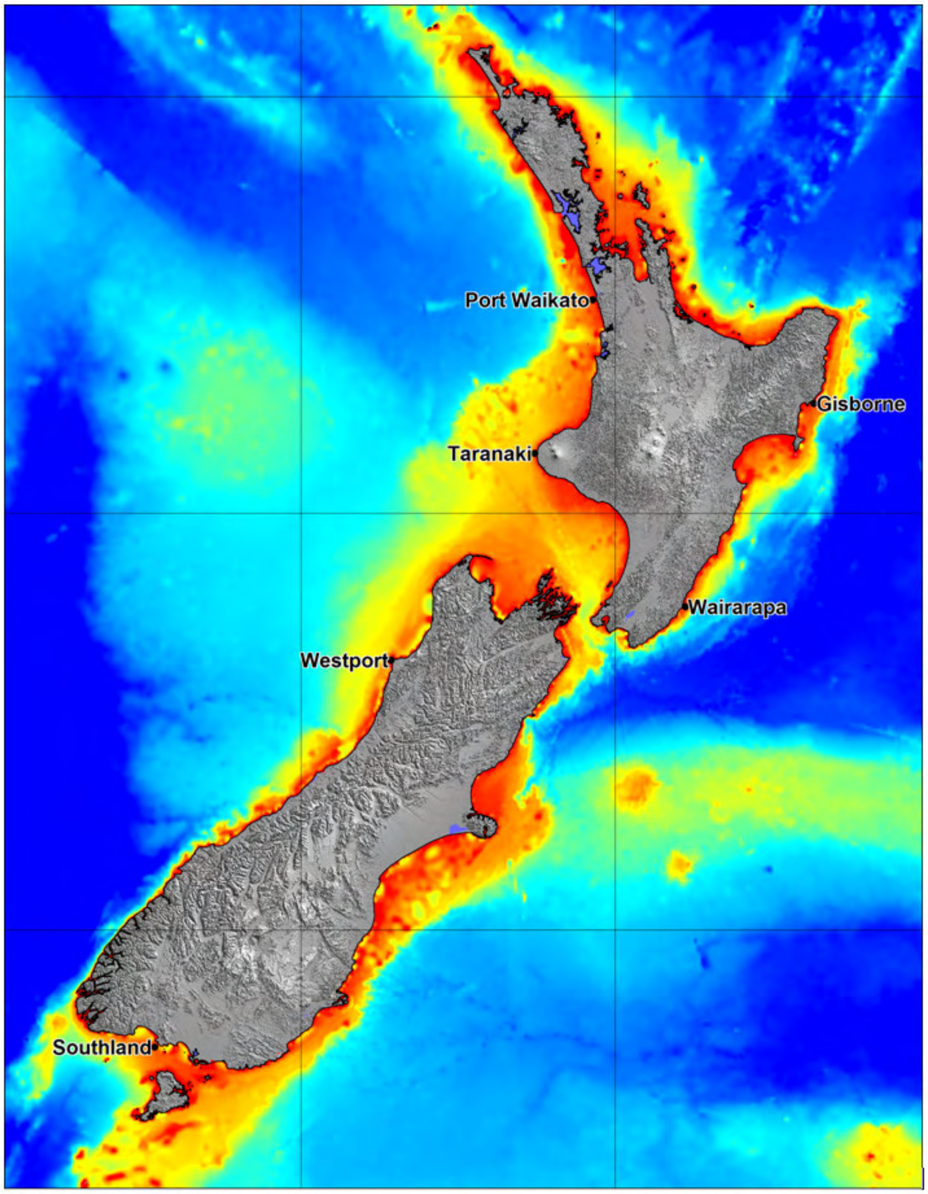


Figure 6.1 Location of the wave power assessment sites

6.2 Summary statistics

Summary statistics of the wave climate, wave energy and wave power for the mean, median and 99th percentile level are presented in Tables 6.2, 6.3 and 6.4, respectively. Of the sites examined, Southland is the most energetic and Gisborne is the least energetic. The West Coast locations (Westport, Taranaki and Port Waikato) all show very similar wave climate and wave power statistics. The Wairarapa location was approximately 25% more energetic than the Gisborne site.

Notably, the East Coast occasionally experiences very energetic wave conditions (see Fig. 5.5), so while the mean wave energy is lower than the West Coast, the East Coast storm conditions have potential to be more severe, which has implications for the engineering design basis for a wave farm. Further, these occasional energetic storms are not a reliable wave power source, and the use of the median annual wave power statistics (Table 6.3) is better statistic for inter-site comparisons. For example, based on Table 6.3 the Wairarapa location has one third the energy resource of the typical West Coast environment.

6.3 Wave height – period statistics

The wave climate may be characterised with a joint probability distribution of the significant wave heights and peak spectral wave periods. These data are an essential requirement for a wave power assessment, and they are presented as parts-per-thousand in Tables 6.5 – 6.10. The data show that Southland and the West Coast locations are dominated by 10-14 s wave conditions, while the East Coast locations (Gisborne and Wairarapa) have slightly lower periods (8-12 s).

6.4 Wave power persistence exceedence statistics

Persistence exceedence tables provide a useful method to examine the duration of the energetic conditions, and these matrices are provided for each of the six assessment sites in Tables 6.11-6.16. As an example interpretation: for the Southland location (Table 6.11) for 12% of the year the wave power is >80 kW/m for periods of 48 hours or more.

6.5 Wave power variability

The natural variability of incident wave power is an important consideration for the planning of electricity generation. To understand the variability of wave power on a daily basis, the hindcast wave power time-series was analysed for the standard deviation from the daily mean, and then normalised to the mean to provide an estimate of the percentage variability. Such variability estimates are provided for each of the six locations (Table 6.2), and a more detailed monthly analysis is provided for the energetic Southland location in Table 6.17. Typically, the daily power variability can be expected to range from 25 - 40%.

Table 6.2 Mean site-specific statistics based on 10-years hindcast data.

Station (6 km offshore)	**Units**	**Southland**	**Westport**	**Taranaki**	**Port Waikato**	**Gisborne**	**Wairarapa**
H_s	m	2.91	2.33	2.26	2.15	1.43	1.72
H_s (swell, T>10s)	m	2.05	1.60	1.51	1.49	0.68	0.89
H_s (sea, T<10s)	m	1.95	1.62	1.60	1.46	1.22	1.42
Wavelength	m	132	153	150	129	108	119
Wave power	$kW.m^{-1}$	53.7	30.9	29.7	27.4	10.8	13.7
Mean daily power variability	%	29.4	25.8	27.0	26.4	38.2	35.1
Pelamis 750 kW generator	kW	228	158	149	129	88	109
Hypothetical Pelamis 1500 kW generator	kW	1354	1316	1275	1236	815	999
Hypothetical SPA 750 kW generator	kW	643	592	572	551	371	441
Surface wave orbital velocity	m/s	1.07	0.76	0.75	0.84	0.60	0.67
Surface wave orbital velocity cubed	m/s	1.72	0.65	0.67	0.86	0.45	0.55

Table 6.3 Median site-specific statistics based on 10-years hindcast data.

Station (6 km offshore)	**Units**	**Southland**	**Westport**	**Taranaki**	**Port Waikato**	**Gisborne**	**Wairarapa**
H_s	m	2.79	2.20	2.13	2.04	1.22	1.53
H_s (swell, T>10s)	m	2.02	1.52	1.45	1.45	0.53	0.74
H_s (sea, T<10s)	m	1.79	1.48	1.46	1.33	1.04	1.26
Wavelength	m	138	156	155	132	110	123
Wave power	$kW.m^{-1}$	40.8	22.6	22.2	21.3	5.2	7.3
Pelamis 750 kW generator	kW	216	130	116	104	38	76
Hypothetical Pelamis 1500 kW generator	kW	1500	1467	1460	1444	730	1116
Hypothetical SPA 750 kW generator	kW	750	627	582	582	325	430
Surface wave orbital velocity	m/s	1.02	0.71	0.70	0.80	0.52	0.60
Surface wave orbital velocity cubed	m/s	1.07	0.36	0.34	0.51	0.14	0.22

Table 6.4 Site-specific statistics at the 99th percentile non-exceedence level based on 10-years hindcast data.

Station (6 km offshore)	**Units**	**Southland**	**Westport**	**Taranaki**	**Port Waikato**	**Gisborne**	**Wairarapa**
H_s	m	6.37	5.22	5.04	4.72	4.23	4.73
H_s (swell, T>10s)	m	5.08	3.90	3.72	3.48	2.70	3.13
H_s (sea, T<10s)	m	4.23	3.84	3.75	3.50	3.60	3.84
Wavelength	m	203	256	243	188	202	233
Wave power	$kW.m^{-1}$	239.5	141.3	136.5	117.8	80.0	96.6
Pelamis 750 kW generator	kW	670	590	586	521	530	590
Hypothetical Pelamis 1500 kW generator	kW	1500	1500	1500	1500	1500	1500
Hypothetical SPA 750 kW generator	kW	750	750	750	750	750	750
Surface wave orbital velocity	m/s	2.17	1.70	1.71	1.81	1.61	1.71
Surface wave orbital velocity cubed	m/s	10.17	4.94	4.97	5.91	4.19	4.97

Table 6.5 Joint probability distribution (parts-per-thousand) of significant wave height and peak spectral wave period for the Southland assessment location.

Location	**Southland**										
	Peak spectral wave period (s)										
Hs (m)	**0-2**	**2-4**	**4-6**	**6-8**	**8-10**	**10-12**	**12-14**	**14-16**	**16-18**	**18-20**	**Total**
> 0 <= 0.5	0	3.1	1.4	1.2	0.9	1.8	0.4	0	0.1	0	**8.9**
> 0.5 <= 1	0	11.3	4.7	3.8	10.7	5.2	1.6	0.3	0.1	0	**37.7**
> 1 <= 1.5	0	0.3	16.7	2.8	19.4	16.1	2.5	0.7	0.1	0	**58.6**
> 1.5 <= 2	0	0	10.7	5.1	28.5	60	10	2.3	0.5	0	**117.1**
> 2 <= 2.5	0	0	2	8.5	19.6	104.6	28.8	5	0.7	0	**169.2**
> 2.5 <= 3	0	0	0	7.9	7.9	100.1	57.1	5.8	1.5	0.1	**180.4**
> 3 <= 3.5	0	0	0	2.9	8.7	65.3	67.2	8.1	0.9	0.1	**153.2**
> 3.5 <= 4	0	0	0	0.6	7.2	30.5	61.3	6.3	0.3	0	**106.2**
> 4 <= 4.5	0	0	0	0.1	3.5	13.3	46.3	6.1	0.1	0	**69.4**
> 4.5 <= 5	0	0	0	0	1.4	8.3	26.3	7	0.1	0	**43.1**
> 5 <= 5.5	0	0	0	0	0.2	4.4	14.2	6.2	0.1	0	**25.1**
> 5.5 <= 6	0	0	0	0	0.1	2.4	7.2	4.8	0	0	**14.5**
> 6 <= 6.5	0	0	0	0	0	1.6	4	2.2	0	0	**7.8**
> 6.5 <= 7	0	0	0	0	0	0.3	2.1	1.2	0	0	**3.6**
> 7 <= 7.5	0	0	0	0	0	0.1	1.3	0.8	0	0	**2.2**
> 7.5 <= 8	0	0	0	0	0	0.1	0.7	0.7	0	0	**1.5**
> 8 <= 8.5	0	0	0	0	0	0	0.4	0.3	0	0	**0.7**
> 8.5 <= 9	0	0	0	0	0	0	0.1	0.3	0	0	**0.4**
> 9 <= 9.5	0	0	0	0	0	0	0	0	0	0	**0**
> 9.5	0	0	0	0	0	0	0	0	0	0	**0**
Total	**0**	**14.7**	**35.5**	**32.9**	**108.1**	**414.1**	**331.5**	**58.1**	**4.5**	**0.2**	**1000**

Table 6.6 Joint probability distribution (parts-per-thousand) of significant wave height and peak spectral wave period for the Westport assessment location.

Location	**Westport**										
	Peak spectral wave period (s)										
Hs (m)	**0-2**	**2-4**	**4-6**	**6-8**	**8-10**	**10-12**	**12-14**	**14-16**	**16-18**	**18-20**	**Total**
> 0 <= 0.5	0	0.3	0.4	0.9	0.4	0.2	0.1	0.2	0.1	0	**2.6**
> 0.5 <= 1	0	0.3	3.9	5.1	12	7.5	1.5	0.7	0.1	0	**31.1**
> 1 <= 1.5	0	0	4	7.9	33.2	65.6	12.7	2.5	0.5	0	**126.4**
> 1.5 <= 2	0	0	1.7	9.9	34.5	132.6	54.6	5.9	1.8	0.1	**241.1**
> 2 <= 2.5	0	0	0.3	9.1	25.7	95	94.1	11.1	1.6	0.1	**237**
> 2.5 <= 3	0	0	0	5.3	14.7	54.8	78.4	10.9	0.9	0.1	**165.1**
> 3 <= 3.5	0	0	0	1.4	10.3	25.4	50.3	9.6	0.3	0	**97.3**
> 3.5 <= 4	0	0	0	0.4	5.8	10.4	22.7	10.1	0.2	0.1	**49.7**
> 4 <= 4.5	0	0	0	0	2.9	6	8.8	6.5	0	0	**24.2**
> 4.5 <= 5	0	0	0	0	1.3	3.8	3.9	3.7	0	0	**12.7**
> 5 <= 5.5	0	0	0	0	0.5	2.5	1.7	1.3	0	0	**6**
> 5.5 <= 6	0	0	0	0	0.1	0.9	0.7	0.9	0	0	**2.6**
> 6 <= 6.5	0	0	0	0	0	0.6	0.4	0.3	0	0	**1.3**
> 6.5 <= 7	0	0	0	0	0	0.2	0.7	0.2	0	0	**1.1**
> 7 <= 7.5	0	0	0	0	0	0	0.3	0.1	0	0	**0.4**
> 7.5 <= 8	0	0	0	0	0	0	0.4	0.2	0	0	**0.6**
> 8 <= 8.5	0	0	0	0	0	0	0.1	0.1	0	0	**0.2**
> 8.5 <= 9	0	0	0	0	0	0	0.1	0.1	0	0	**0.2**
> 9 <= 9.5	0	0	0	0	0	0	0.1	0.1	0	0	**0.2**
> 9.5	0	0	0	0	0	0	0	0.2	0	0	**0.2**
Total	**0**	**0.6**	**10.3**	**40**	**141.4**	**405.5**	**331.6**	**64.7**	**5.5**	**0.4**	**1000**

Table 6.7 Joint probability distribution (parts-per-thousand) of significant wave height and peak spectral wave period for the Taranaki assessment location.

Location	**Taranaki**										
	Peak spectral wave period (s)										
Hs (m)	**0-2**	**2-4**	**4-6**	**6-8**	**8-10**	**10-12**	**12-14**	**14-16**	**16-18**	**18-20**	**Total**
> 0 <= 0.5	0	0.9	1.3	1.7	3.2	1.3	0.4	0.3	0	0	**9.1**
> 0.5 <= 1	0	1.2	4	4.6	11.6	13.9	3.1	0.8	0.3	0.1	**39.6**
> 1 <= 1.5	0	0	4.7	9	29.2	74.9	17.3	2.8	0.8	0.1	**138.8**
> 1.5 <= 2	0	0	2.8	12.5	28.2	117.7	72	8.8	1.9	0.1	**244**
> 2 <= 2.5	0	0	0.1	14.1	18.4	79.1	104.3	13.1	1.8	0.2	**231.1**
> 2.5 <= 3	0	0	0	8.4	15.8	40.1	79.2	12.6	0.5	0	**156.6**
> 3 <= 3.5	0	0	0	1.9	13.5	17.9	46.3	12.4	0.3	0.1	**92.4**
> 3.5 <= 4	0	0	0	0.4	7.5	7.5	19.6	9.9	0.2	0.1	**45.2**
> 4 <= 4.5	0	0	0	0	4.1	5.6	7	6	0	0	**22.7**
> 4.5 <= 5	0	0	0	0	1.2	3	2.8	3.2	0	0	**10.2**
> 5 <= 5.5	0	0	0	0	0.3	1.8	1.1	1.4	0	0	**4.6**
> 5.5 <= 6	0	0	0	0	0.1	1.2	0.7	0.4	0	0	**2.4**
> 6 <= 6.5	0	0	0	0	0	0.5	0.4	0.2	0	0	**1.1**
> 6.5 <= 7	0	0	0	0	0	0.4	0.4	0.1	0	0	**0.9**
> 7 <= 7.5	0	0	0	0	0	0	0.3	0.1	0	0	**0.4**
> 7.5 <= 8	0	0	0	0	0	0	0.1	0.1	0	0	**0.2**
> 8 <= 8.5	0	0	0	0	0	0	0	0	0	0	**0**
> 8.5 <= 9	0	0	0	0	0	0	0.1	0.1	0	0	**0.2**
> 9 <= 9.5	0	0	0	0	0	0	0	0.1	0	0	**0.1**
> 9.5	0	0	0	0	0	0	0	0.1	0	0	**0.1**
Total	**0**	**2.1**	**12.9**	**52.6**	**133.1**	**364.9**	**355.1**	**72.5**	**5.8**	**0.7**	**1000**

Table 6.8 Joint probability distribution (parts-per-thousand) of significant wave height and peak spectral wave period for the Port Waikato assessment location.

Location	**Port Waikato**										
	Peak spectral wave period (s)										
Hs (m)	**0-2**	**2-4**	**4-6**	**6-8**	**8-10**	**10-12**	**12-14**	**14-16**	**16-18**	**18-20**	**Total**
> 0 <= 0.5	0.2	3.2	0.3	1.7	2.1	0.6	0.3	0.2	0.2	0	**8.8**
> 0.5 <= 1	0	5.4	2.9	2.6	13.4	15.3	4.2	1	0.5	0.2	**45.5**
> 1 <= 1.5	0	1	8.5	7.4	26.4	83.4	23.1	4.4	1.3	0.1	**155.6**
> 1.5 <= 2	0	0	3.8	11	20.4	131.8	88.2	12	2.1	0.1	**269.4**
> 2 <= 2.5	0	0	0.2	6.5	11.3	71.6	128.3	16	1.9	0	**235.8**
> 2.5 <= 3	0	0	0	3.9	9.3	28.2	86.9	17.7	1	0.1	**147.1**
> 3 <= 3.5	0	0	0	0.8	6.5	11.1	38.9	16.6	0.3	0.1	**74.3**
> 3.5 <= 4	0	0	0	0	3.4	5.6	13.7	10.2	0.2	0	**33.1**
> 4 <= 4.5	0	0	0	0	1.6	4.6	4.6	5.4	0.1	0	**16.3**
> 4.5 <= 5	0	0	0	0	0.4	2.8	2.3	2	0.1	0	**7.6**
> 5 <= 5.5	0	0	0	0	0	1.5	0.9	0.7	0	0	**3.1**
> 5.5 <= 6	0	0	0	0	0	0.8	0.4	0.4	0	0	**1.6**
> 6 <= 6.5	0	0	0	0	0	0.2	0.6	0.2	0	0	**1**
> 6.5 <= 7	0	0	0	0	0	0	0.3	0.2	0	0	**0.5**
> 7 <= 7.5	0	0	0	0	0	0	0.2	0.1	0	0	**0.3**
> 7.5 <= 8	0	0	0	0	0	0	0	0	0	0	**0**
> 8 <= 8.5	0	0	0	0	0	0	0	0	0	0	**0**
> 8.5 <= 9	0	0	0	0	0	0	0	0	0	0	**0**
> 9 <= 9.5	0	0	0	0	0	0	0	0	0	0	**0**
> 9.5	0	0	0	0	0	0	0	0	0	0	**0**
Total	**0.2**	**9.6**	**15.7**	**33.9**	**94.8**	**357.5**	**392.9**	**87.1**	**7.7**	**0.6**	**1000**

Table 6.9 Joint probability distribution (parts-per-thousand) of significant wave height and peak spectral wave period for the Gisborne assessment location.

Location	**Gisborne**										
	Peak spectral wave period (s)										
Hs (m)	**0-2**	**2-4**	**4-6**	**6-8**	**8-10**	**10-12**	**12-14**	**14-16**	**16-18**	**18-20**	**Total**
> 0 <= 0.5	0.2	10.3	1.9	8	5.9	12	10.5	3.1	0.4	0	**52.3**
> 0.5 <= 1	0	36.9	11.8	36.5	59.5	92.9	56.6	5.6	0.2	0	**300**
> 1 <= 1.5	0	2.7	17.1	35.8	95.1	80.2	53.6	3.1	0	0	**287.6**
> 1.5 <= 2	0	0	6.4	26.2	64.3	45.5	19.1	1.2	0	0	**162.7**
> 2 <= 2.5	0	0	0.6	17.3	31.5	35.7	7.9	0.8	0	0	**93.8**
> 2.5 <= 3	0	0	0	8.5	14.7	22.1	5.4	0.3	0	0	**51**
> 3 <= 3.5	0	0	0	2.2	9.6	11.3	3.3	0.1	0	0	**26.5**
> 3.5 <= 4	0	0	0	0.1	5.1	5	2	0.1	0	0	**12.3**
> 4 <= 4.5	0	0	0	0	2.3	2.7	1.1	0	0	0	**6.1**
> 4.5 <= 5	0	0	0	0	0.7	2	0.6	0	0	0	**3.3**
> 5 <= 5.5	0	0	0	0	0.2	1.2	0.4	0	0	0	**1.8**
> 5.5 <= 6	0	0	0	0	0	0.6	0.2	0	0	0	**0.8**
> 6 <= 6.5	0	0	0	0	0	0.4	0.3	0	0	0	**0.7**
> 6.5 <= 7	0	0	0	0	0	0.1	0.4	0	0	0	**0.5**
> 7 <= 7.5	0	0	0	0	0	0.1	0.3	0	0	0	**0.4**
> 7.5 <= 8	0	0	0	0	0	0	0.1	0.1	0	0	**0.2**
> 8 <= 8.5	0	0	0	0	0	0	0	0.1	0	0	**0.1**
> 8.5 <= 9	0	0	0	0	0	0	0	0.1	0	0	**0.1**
> 9 <= 9.5	0	0	0	0	0	0	0	0	0	0	**0**
> 9.5	0	0	0	0	0	0	0	0	0	0	**0**
Total	**0.2**	**49.9**	**37.8**	**134.6**	**288.9**	**311.8**	**161.8**	**14.6**	**0.6**	**0**	**1000**

Table 6.10 Joint probability distribution (parts-per-thousand) of significant wave height and peak spectral wave period for the Wairarapa assessment location.

Location	**Wairarapa**										
	Peak spectral wave period (s)										
Hs (m)	**0-2**	**2-4**	**4-6**	**6-8**	**8-10**	**10-12**	**12-14**	**14-16**	**16-18**	**18-20**	**Total**
> 0 <= 0.5	0	1.1	1.2	1	0.8	1.3	1.1	0.2	0	0	**6.7**
> 0.5 <= 1	0	20.4	11.9	23.5	21.9	42.6	23.2	4.1	0.4	0	**148**
> 1 <= 1.5	0	8.5	29.7	37.3	75.4	116.4	55.1	5.8	0.3	0	**328.5**
> 1.5 <= 2	0	0	9.9	25.9	67.6	84	44.2	4.3	0.1	0	**236**
> 2 <= 2.5	0	0	1.1	17.2	31.5	55.8	29.1	2.8	0	0	**137.5**
> 2.5 <= 3	0	0	0	9.8	16.5	28.4	12.7	1.1	0	0	**68.5**
> 3 <= 3.5	0	0	0	2.7	11.2	13.4	7.2	1	0	0	**35.5**
> 3.5 <= 4	0	0	0	0.4	7.4	6.6	3.6	0.2	0	0	**18.2**
> 4 <= 4.5	0	0	0	0.1	2.9	4.3	1.4	0.1	0	0	**8.8**
> 4.5 <= 5	0	0	0	0	0.9	2.7	0.6	0.1	0	0	**4.3**
> 5 <= 5.5	0	0	0	0	0.3	2.8	0.6	0.1	0	0	**3.8**
> 5.5 <= 6	0	0	0	0	0.1	1.4	0.4	0	0	0	**1.9**
> 6 <= 6.5	0	0	0	0	0	0.7	0.4	0	0	0	**1.1**
> 6.5 <= 7	0	0	0	0	0	0.1	0.2	0	0	0	**0.3**
> 7 <= 7.5	0	0	0	0	0	0	0.1	0	0	0	**0.1**
> 7.5 <= 8	0	0	0	0	0	0.1	0.2	0	0	0	**0.3**
> 8 <= 8.5	0	0	0	0	0	0	0	0	0	0	**0**
> 8.5 <= 9	0	0	0	0	0	0	0.1	0	0	0	**0.1**
> 9 <= 9.5	0	0	0	0	0	0	0	0	0	0	**0**
> 9.5	0	0	0	0	0	0	0.2	0	0	0	**0.2**
Total	**0**	**30**	**53.8**	**117.9**	**236.5**	**360.6**	**180.4**	**19.8**	**0.8**	**0**	**1000**

Table 6.11 Southland wave power – annual persistence exceedence (%).

Spectral wave power (kW.m^{-1})	**Duration (hours)**													
	> 12	**> 24**	**> 36**	**> 48**	**> 60**	**> 72**	**> 84**	**> 96**	**> 108**	**> 120**	**> 132**	**> 144**	**> 156**	**> 168**
>=0	100	100	100	100	100	100	100	100	100	100	100	100	100	100
>=20	75	73.84	72.16	70.44	68.56	66.38	63.99	61.29	57.8	54.48	51.6	48.58	45.79	43.73
>=40	50.12	47.93	44.88	41.46	38.05	34.56	31.48	28.39	26.38	23.1	20.62	17.92	15.33	13.48
>=60	30.91	28.55	25.34	22.4	19.64	16.41	14.32	11.63	9.76	7.52	6.21	5.09	4.4	4.22
>=80	19.41	17.27	14.9	12.09	9.75	7.77	5.33	3.89	3.41	2.88	2.31	1.69	1.52	1.14
>=100	12.54	10.65	8.55	6.73	5.1	3.96	2.54	2.04	1.57	1.04	0.76	0.76	0.41	0.23
>=120	7.98	6.65	5.05	3.73	2.5	1.33	0.9	0.49	0.26	0	0	0	0	0
>=140	5.38	4.19	3.2	1.86	1.22	0.31	0.31	0.12	0	0	0	0	0	0
>=160	3.65	2.47	1.59	0.98	0.55	0.19	0.1	0	0	0	0	0	0	0
>=180	2.37	1.56	0.84	0.49	0.1	0.1	0	0	0	0	0	0	0	0
>=200	1.56	1.03	0.4	0.21	0.09	0.09	0	0	0	0	0	0	0	0
>=220	1.02	0.59	0.32	0.19	0.07	0	0	0	0	0	0	0	0	0
>=240	0.68	0.38	0.22	0.12	0	0	0	0	0	0	0	0	0	0
>=260	0.55	0.26	0.16	0	0	0	0	0	0	0	0	0	0	0
>=280	0.39	0.16	0.1	0	0	0	0	0	0	0	0	0	0	0
>=300	0.27	0.12	0.04	0	0	0	0	0	0	0	0	0	0	0
>=320	0.22	0.1	0	0	0	0	0	0	0	0	0	0	0	0
>=340	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0
>=360	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0
>=380	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0
>=400	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=420	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=440	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=460	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=480	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=500	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.12 Westport wave power – annual persistence exceedence (%).

Spectral wave power ($kW.m^{-1}$)	**Duration (hours)**													
	> 12	**> 24**	**> 36**	**> 48**	**> 60**	**> 72**	**> 84**	**> 96**	**> 108**	**> 120**	**> 132**	**> 144**	**> 156**	**> 168**
>=0	100	100	100	100	100	100	100	100	100	100	100	100	100	100
>=20	54.69	52.61	50.37	46.99	43.42	39.46	34.57	32.06	28.76	26.27	23.64	20.77	19.2	17.34
>=40	22.7	20.67	17.35	14.32	11.14	9.07	7.28	6.15	5.09	3.91	3.17	2.53	1.84	1.84
>=60	10.04	8.37	6.41	5.02	2.79	2.11	1.38	0.97	0.62	0.49	0.34	0.18	0.18	0
>=80	5.04	3.56	2.63	1.48	0.49	0.34	0.34	0.13	0.13	0	0	0	0	0
>=100	2.63	2.01	0.98	0.33	0.09	0.09	0	0	0	0	0	0	0	0
>=120	1.5	0.91	0.4	0.06	0	0	0	0	0	0	0	0	0	0
>=140	0.79	0.39	0.15	0	0	0	0	0	0	0	0	0	0	0
>=160	0.5	0.23	0.09	0	0	0	0	0	0	0	0	0	0	0
>=180	0.36	0.13	0.05	0	0	0	0	0	0	0	0	0	0	0
>=200	0.24	0.11	0.04	0	0	0	0	0	0	0	0	0	0	0
>=220	0.22	0.07	0	0	0	0	0	0	0	0	0	0	0	0
>=240	0.2	0.07	0	0	0	0	0	0	0	0	0	0	0	0
>=260	0.16	0.07	0	0	0	0	0	0	0	0	0	0	0	0
>=280	0.12	0.06	0	0	0	0	0	0	0	0	0	0	0	0
>=300	0.09	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=320	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0
>=340	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0
>=360	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0
>=380	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0
>=400	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=420	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=440	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=460	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=480	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=500	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.13 Taranaki wave power – annual persistence exceedence (%).

Spectral wave power (kW.m^{-1})	**Duration (hours)**													
	> 12	**> 24**	**> 36**	**> 48**	**> 60**	**> 72**	**> 84**	**> 96**	**> 108**	**> 120**	**> 132**	**> 144**	**> 156**	**> 168**
>=0	100	100	100	100	100	100	100	100	100	100	100	100	100	100
>=20	53.97	51.94	49.59	47.14	43.69	39.61	35.33	32.31	29.97	27.7	25.36	23.61	21.19	20.07
>=40	21.8	19.54	16.83	14.08	11	9.24	7.15	5.82	5.12	3.94	3.05	2.25	1.73	1.55
>=60	9.25	7.95	5.73	4.47	2.42	1.58	0.95	0.85	0.85	0.46	0.17	0.17	0	0
>=80	4.44	3.22	2.3	1.02	0.46	0.3	0.12	0.12	0	0	0	0	0	0
>=100	2.2	1.6	0.67	0.38	0.2	0.2	0.11	0	0	0	0	0	0	0
>=120	1.26	0.78	0.41	0.17	0.11	0.11	0.11	0	0	0	0	0	0	0
>=140	0.68	0.35	0.1	0	0	0	0	0	0	0	0	0	0	0
>=160	0.38	0.2	0.05	0	0	0	0	0	0	0	0	0	0	0
>=180	0.28	0.14	0	0	0	0	0	0	0	0	0	0	0	0
>=200	0.22	0.07	0	0	0	0	0	0	0	0	0	0	0	0
>=220	0.17	0.07	0	0	0	0	0	0	0	0	0	0	0	0
>=240	0.14	0.07	0	0	0	0	0	0	0	0	0	0	0	0
>=260	0.1	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=280	0.07	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=300	0.05	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=320	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0
>=340	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0
>=360	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=380	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=400	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=420	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=440	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=460	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=480	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=500	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.14 Port Waikato wave power – annual persistence exceedence (%).

Spectral wave power (kW.m^{-1})	**Duration (hours)**													
	> 12	**> 24**	**> 36**	**> 48**	**> 60**	**> 72**	**> 84**	**> 96**	**> 108**	**> 120**	**> 132**	**> 144**	**> 156**	**> 168**
>=0	100	100	100	100	100	100	100	100	100	100	100	100	100	100
>=20	52.52	50.95	48.81	46.01	42.43	39.09	35.73	32.41	30.3	28.21	25.9	23.51	21.43	19.01
>=40	19.47	17.5	15.08	12.26	9.96	7.48	5.68	4.62	3.69	3.29	2.7	1.9	0.87	0.69
>=60	7.54	6.11	4.78	3.3	1.54	1.31	0.52	0.52	0.39	0.14	0	0	0	0
>=80	3.12	2.35	1.41	0.58	0.27	0.2	0.11	0	0	0	0	0	0	0
>=100	1.46	0.89	0.47	0.27	0.16	0	0	0	0	0	0	0	0	0
>=120	0.74	0.4	0.19	0	0	0	0	0	0	0	0	0	0	0
>=140	0.46	0.18	0.04	0	0	0	0	0	0	0	0	0	0	0
>=160	0.27	0.11	0	0	0	0	0	0	0	0	0	0	0	0
>=180	0.16	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=200	0.12	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=220	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0
>=240	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0
>=260	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=280	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=300	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=320	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=340	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=360	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=380	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=400	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=420	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=440	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=460	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=480	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=500	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.15 Gisborne wave power – annual persistence exceedence (%).

Spectral wave power (kW.m^{-1})	**Duration (hours)**													
	> 12	**> 24**	**> 36**	**> 48**	**> 60**	**> 72**	**> 84**	**> 96**	**> 108**	**> 120**	**> 132**	**> 144**	**> 156**	**> 168**
>=0	100	100	100	100	100	100	100	100	100	100	100	100	100	100
>=20	13.22	11.01	8.94	7.49	6.19	5.28	4.63	3.91	2.85	2.33	1.75	1.27	1.27	0.54
>=40	4.08	2.94	2.25	1.51	0.81	0.58	0.12	0.12	0	0	0	0	0	0
>=60	1.5	0.97	0.58	0.18	0	0	0	0	0	0	0	0	0	0
>=80	0.79	0.43	0.14	0	0	0	0	0	0	0	0	0	0	0
>=100	0.51	0.24	0.05	0	0	0	0	0	0	0	0	0	0	0
>=120	0.31	0.17	0.04	0	0	0	0	0	0	0	0	0	0	0
>=140	0.25	0.13	0	0	0	0	0	0	0	0	0	0	0	0
>=160	0.16	0.04	0	0	0	0	0	0	0	0	0	0	0	0
>=180	0.14	0.04	0	0	0	0	0	0	0	0	0	0	0	0
>=200	0.12	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=220	0.09	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=240	0.05	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=260	0.05	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=280	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=300	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=320	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=340	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=360	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=380	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=400	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=420	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=440	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=460	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=480	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=500	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.16 Wairarapa wave power – annual persistence exceedence (%).

Spectral wave power (kW.m^{-1})	**Duration (hours)**													
	> 12	**> 24**	**> 36**	**> 48**	**> 60**	**> 72**	**> 84**	**> 96**	**> 108**	**> 120**	**> 132**	**> 144**	**> 156**	**> 168**
>=0	100	100	100	100	100	100	100	100	100	100	100	100	100	100
>=20	18.46	15.34	12.62	10.83	9.03	7.64	6.55	5.51	4.43	3.65	3.35	2.88	2.53	1.78
>=40	5.59	3.99	2.81	1.84	1.36	1.04	0.77	0.77	0.65	0.51	0.37	0.21	0.21	0.21
>=60	2.3	1.35	0.72	0.43	0.17	0.09	0	0	0	0	0	0	0	0
>=80	1.12	0.56	0.26	0.12	0	0	0	0	0	0	0	0	0	0
>=100	0.65	0.42	0.15	0	0	0	0	0	0	0	0	0	0	0
>=120	0.42	0.25	0.04	0	0	0	0	0	0	0	0	0	0	0
>=140	0.26	0.12	0.04	0	0	0	0	0	0	0	0	0	0	0
>=160	0.2	0.11	0	0	0	0	0	0	0	0	0	0	0	0
>=180	0.17	0.07	0	0	0	0	0	0	0	0	0	0	0	0
>=200	0.12	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=220	0.09	0.03	0	0	0	0	0	0	0	0	0	0	0	0
>=240	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0
>=260	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0
>=280	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0
>=300	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0
>=320	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=340	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=360	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=380	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=400	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=420	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
>=440	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=460	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=480	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>=500	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.17 Monthly wave height and spectral wave power statistics for the Southland assessment location.

	Mean Hs (m)	**Median Hs (m)**	**Mean spectral wave power (kW.m^{-1})**	**Median spectral wave power (kW.m^{-1})**	**Mean daily wave power variability (%)**
Jan	2.49	2.41	35.7	27.9	29.4
Feb	2.67	2.56	42.2	33.2	28.6
Mar	2.87	2.63	49.8	35.3	27.3
Apr	3.12	2.96	62.8	48.4	28.7
May	3.20	3.13	67.1	50.6	29.5
Jun	3.21	3.01	69.0	47.6	28.9
Jul	2.96	2.92	57.0	47.6	27.1
Aug	3.05	3.02	61.2	49.3	30.4
Sep	3.13	3.07	62.6	48.6	32.9
Oct	3.00	2.93	57.8	45.9	31.2
Nov	2.76	2.70	43.6	35.7	28.7
Dec	2.45	2.37	35.3	26.8	30.5
Annual	2.91	2.79	53.7	40.8	29.4

7 TIDAL ENERGY RESOURCES

7.1 New Zealand scale

The open-ocean tidal energy resources in New Zealand are represented in Figures 7.1 and 7.2. These plots show the depth-averaged flows associated with the Mean Spring Tides (M2+S2) and the Highest Astronomical Tides, respectively. There are three regions with accelerated flows; Cook Strait, Cape Reinga and the waters surrounding Stewart Island. The tidal resources in Cook Strait and Foveaux Strait are further considered in the following sections.

7.2 Cook Strait

The tidal energy resources within the Cook Strait are presented in Figures 7.3 and 7.4, showing the depth-averaged flows associated with the Spring Tide (M2+S2) and the Highest Astronomical Tide, respectively.

7.3 Foveaux Strait

The tidal energy resources within the Foveaux Strait are presented in Figures 7.5 and 7.6, showing the depth-averaged flows associated with the Spring Tide (M2+S2) and the Highest Astronomical Tide, respectively.

7.4 Tidal power simulations

Tidal power simulations have been undertaken at six locations; five in the Cook Strait and one in Foveaux Strait, as shown on Figures 7.7 and 7.8. At each location, the time-series of the depth-averaged tidal flows (at 15 minute intervals) has been converted to electrical power using the methods defined in Section 4. Two single-turbine tidal power devices have been simulated, as described in Table 4.1. The results are summarized in Table 7.1.

Table 7.1 Tidal energy site assessment results. Devices 1 and 2 are specified in Table 4.1, and the site locations are shown on Figures 7.7 and 7.8.

Parameter	Units	CS1	CS2	CS3	CS4	CS5	FX1
Mean power of the resource	**Wm^{-2}**	1,660	3,610	1,555	5,190	1,095	304
Device 1							
Rated time	%	4.3	14.9	1.9	22.3	2.0	0.0
Working time	%	63.6	79.6	69.8	80.0	56.5	45.7
Mean annual power	**kW**	105.0	200.0	105.5	229.3	71.5	19.4
Mean annual production	**MWh**	919.3	1752.00	923.8	2009.1	626.1	169.8
Device 2							
Rated time	%	4.3	14.9	1.9	22.3	2.0	0.0
Working time	%	58.3	75.9	65.0	76.6	50.6	36.9
Mean annual power	**kW**	48.8	93.4	49.6	107.2	33.0	8.5
Mean annual production	**MWh**	427.3	818.2	434.1	938.8	289.5	74.0

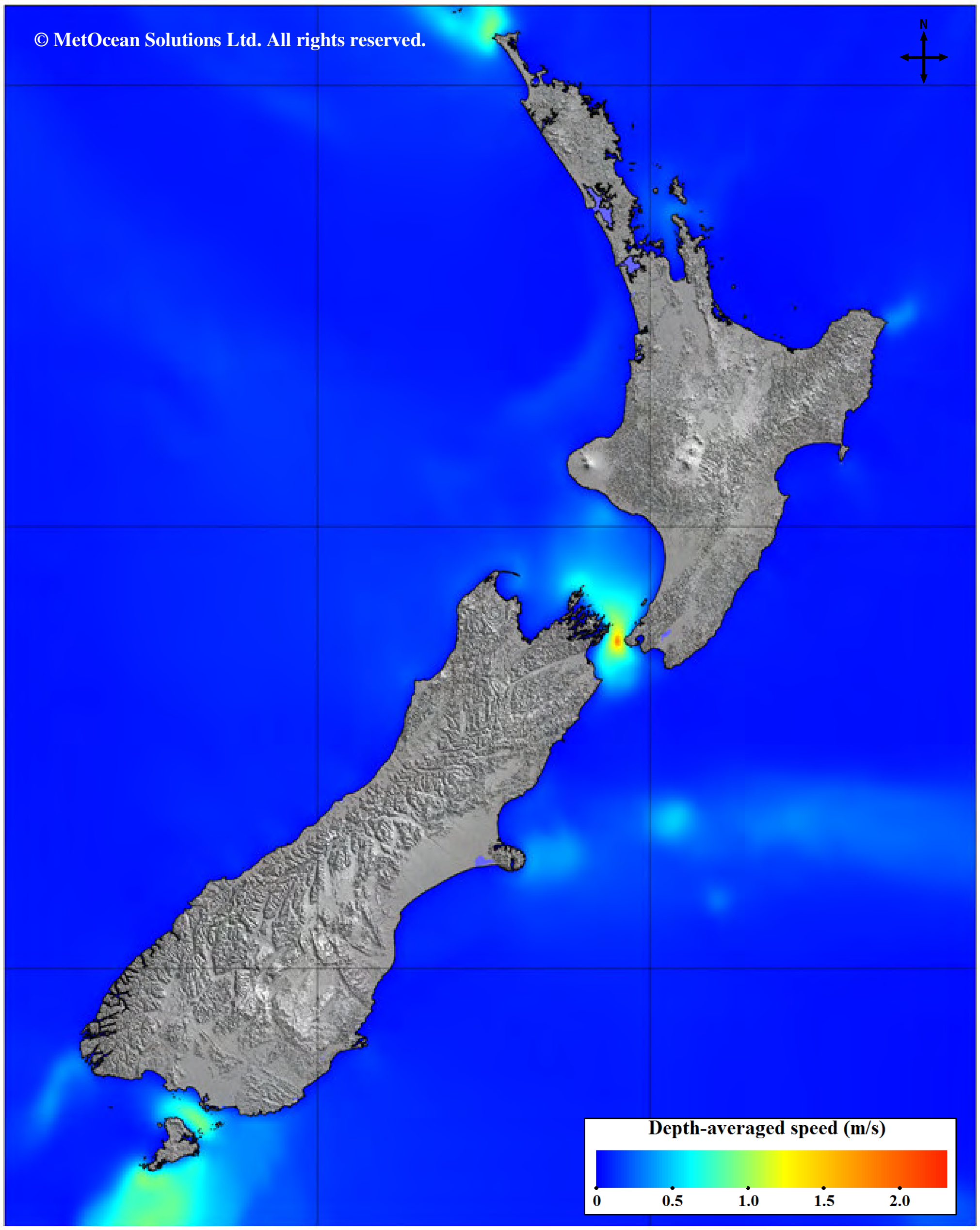


Figure 7.1 Depth-averaged tidal current speeds for the Mean Spring flows

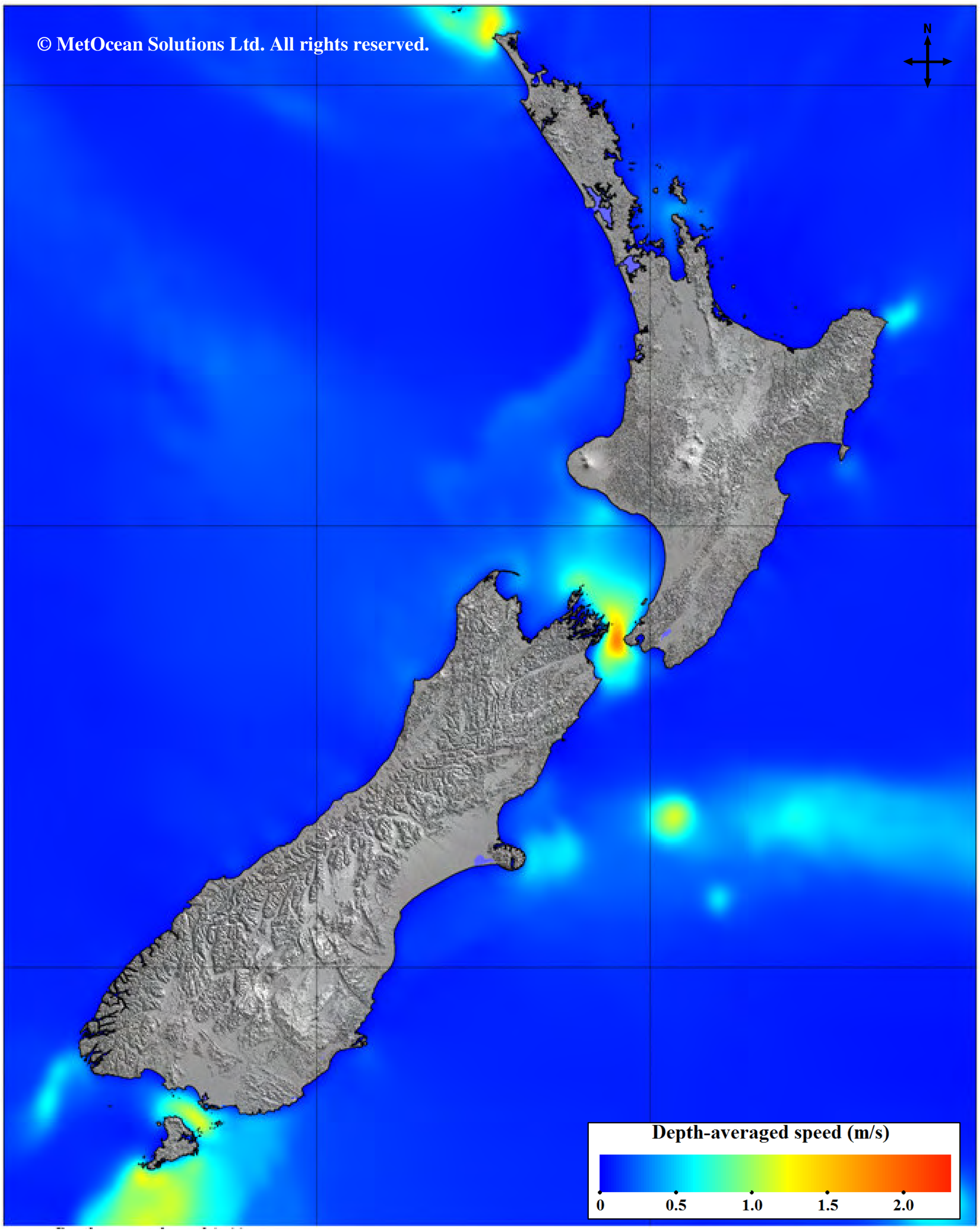


Figure 7.2 Depth-averaged tidal current speeds for the Highest Astronomical flows

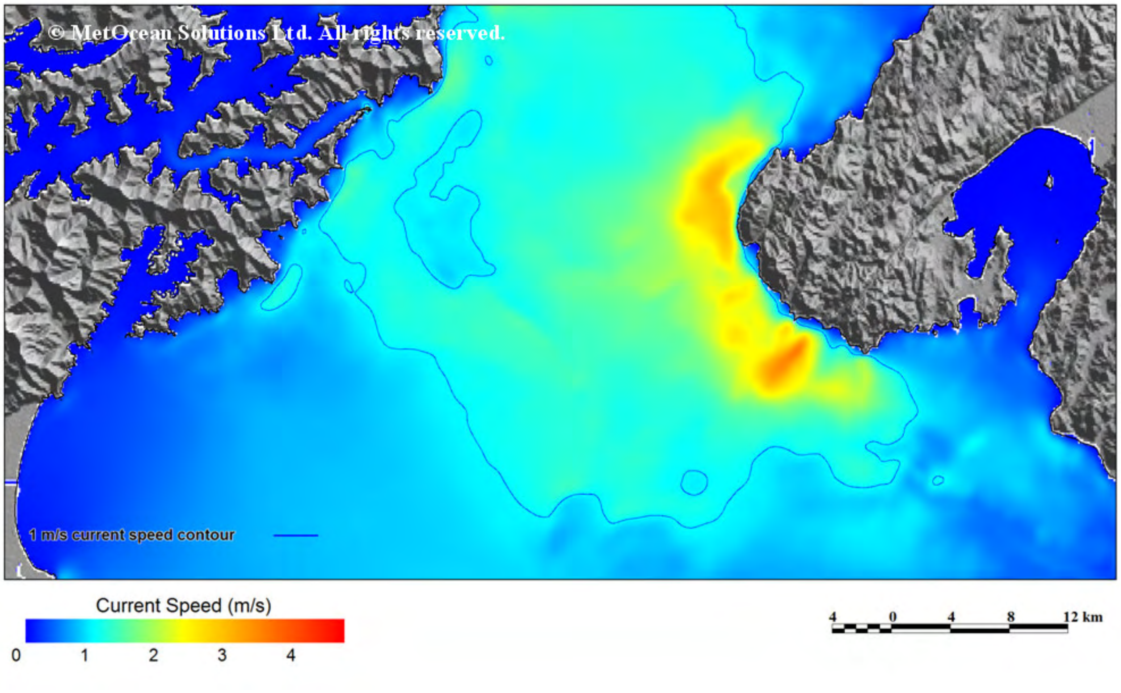


Figure 7.3 Depth-averaged tidal current speeds for the Spring Tide flows in the Cook Strait, including the 1 m/s speed contour.

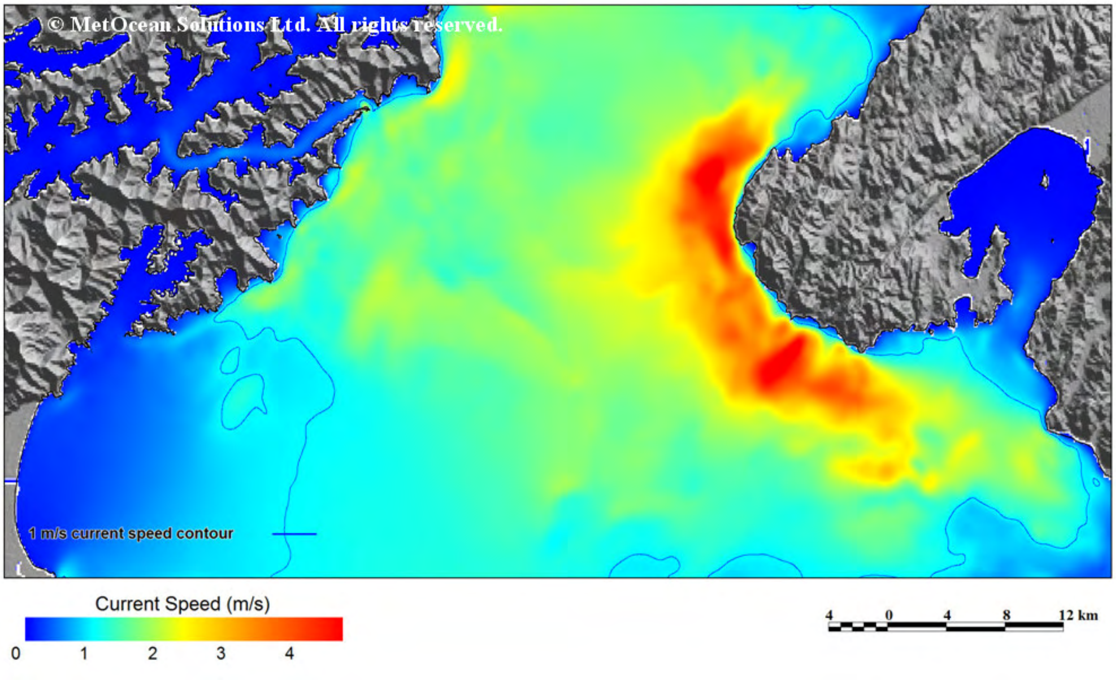


Figure 7.4 Depth-averaged tidal current speeds for the Highest Astronomical Tidal flows in the Cook Strait, including the 1 m/s speed contour.

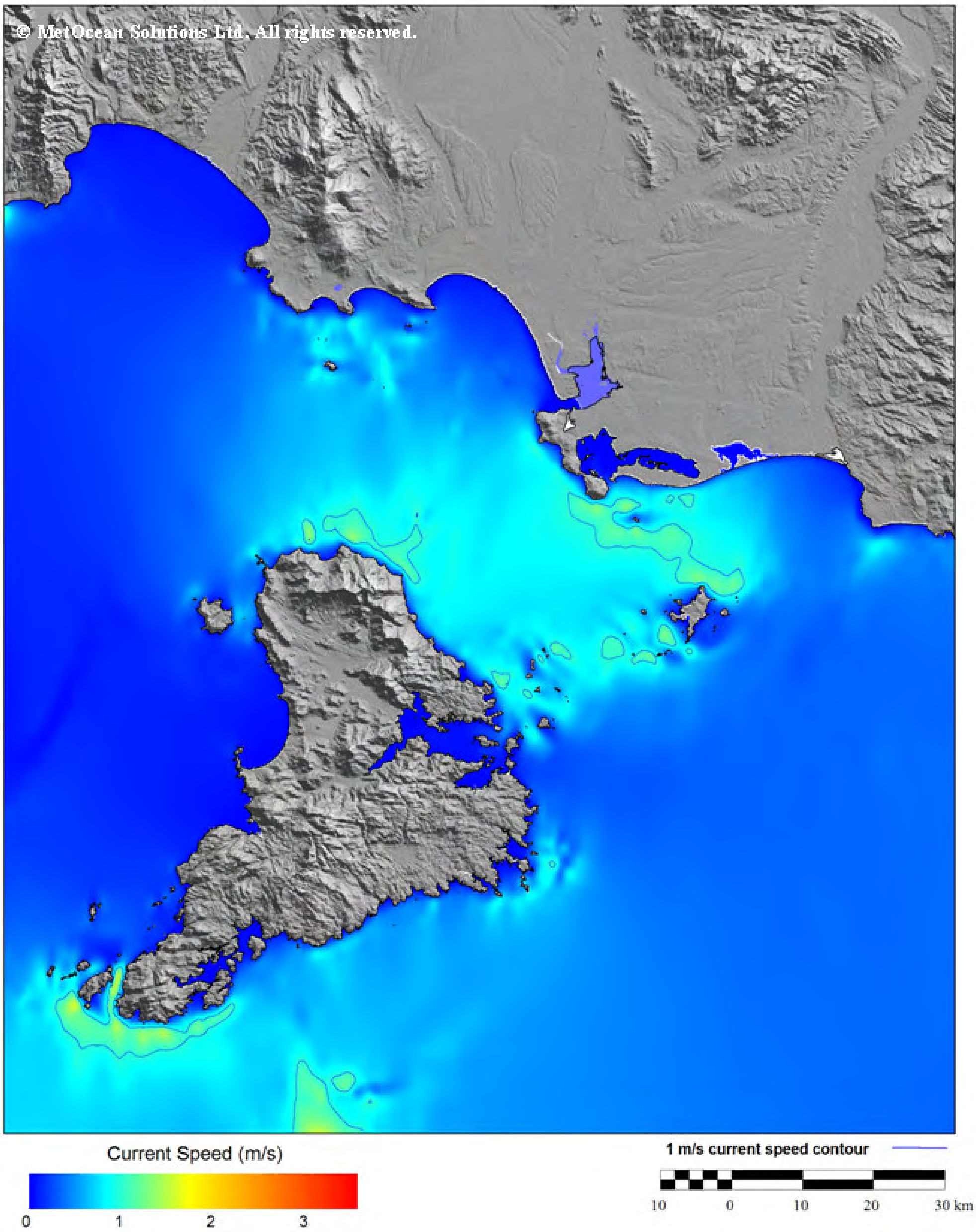


Figure 7.5 Depth-averaged tidal current speeds for the Spring Tidal flows in the Foveaux Strait region, including the 1 m/s speed contour.

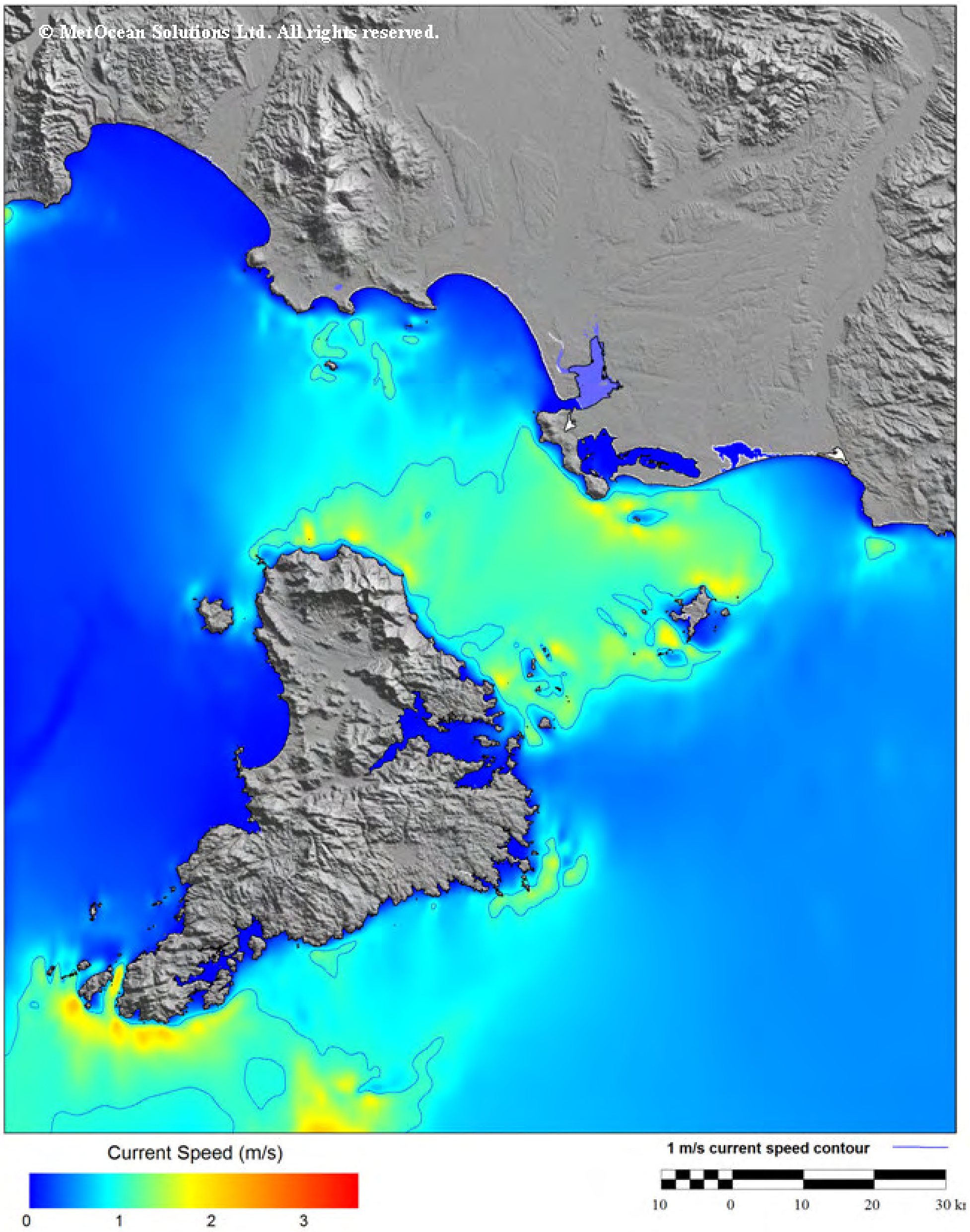


Figure 7.6 Depth-averaged tidal current speeds for the Highest Astronomical Tidal flows in the Foveaux Strait region, including the 1 m/s speed contour.

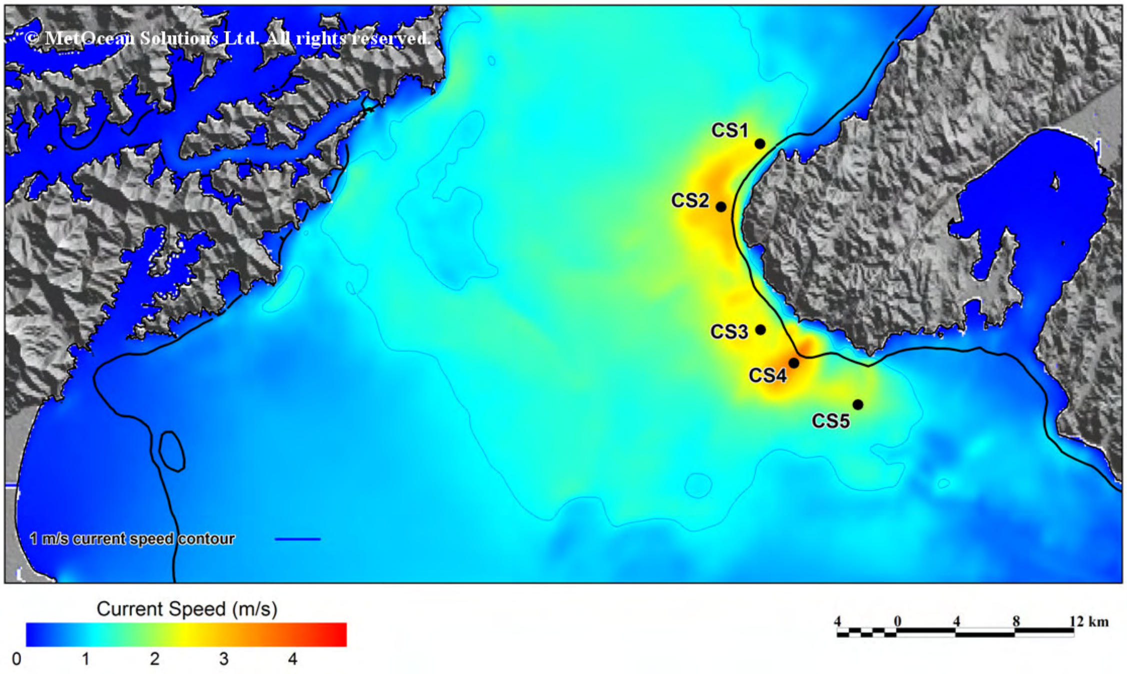


Figure 7.7 The output locations in the Cook Strait region for detailed tidal power generation simulation. The Spring Tidal flows are also shown, along with the 1 m/s speed contour and the 25 m water depth contour.

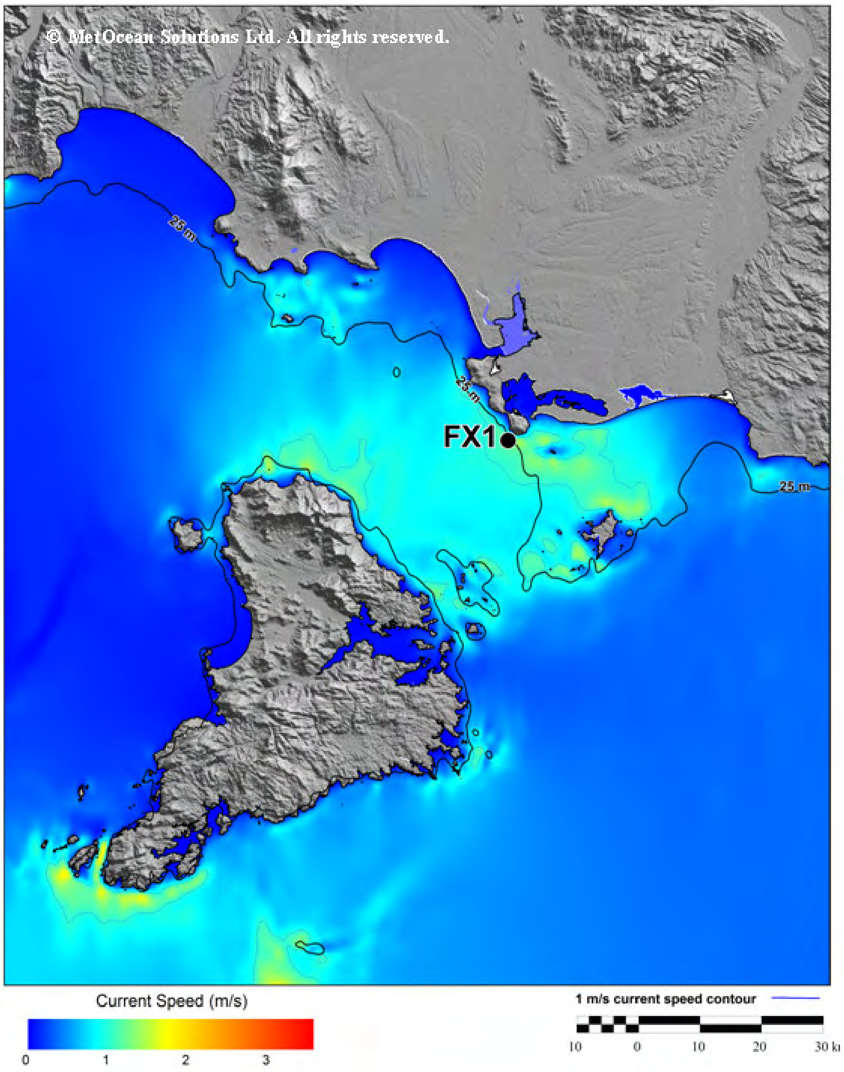


Figure 7.8 The output location in the Foveaux Strait region for detailed tidal power generation simulation. The Spring Tidal flows are also shown, along with the 1 m/s speed contour and the 25 m water depth contour.

8 SUMMARY

An investigation of the open ocean marine energy resources in New Zealand waters has been undertaken. The scope has utilised the following methods:

- A region-scale 10-year numerical wave hindcast for New Zealand, with detailed validation for wave statistics and wave power;
- Depth-averaged tidal current modelling of New Zealand waters, with high-resolution modelling of the Cook Strait and Foveaux Strait regions;

The specific deliverables that have been produced are:

- Summary maps of the open-coast tidal resource, wave climate, potential wave power, and energy output for generic wave conversion devices.
- Detailed analysis of two potential tidal energy regions and six wave energy sites, considering the environmental statistics, probable power output, daily and seasonal variability and time-domain analyses.

The summary modelling results are:

- There is a mean annual wave power resource of at least 30 $kW.m^{-1}$ available within about 15 km of the shoreline along most of the West Coast of New Zealand, excepting the Western Cook Strait region and the North Taranaki Bight. The most energetic wave power location is along the Southland coast, from Fiordland to the west of Stewart Island. Along the East Coast of New Zealand, only the Catlins region in South Otago has an equivalent resource to the West Coast. In the North Island, the coastline from Wairarapa to East Cape is the next most energetic region, with around one third of the median energy of the West Coast.
- There are three locations in New Zealand with an open-coast tidal resource; Cook Strait, Cape Reinga and the waters surrounding Stewart Island. The mean annual Cook Strait resource is as high as 5000 Wm^{-2}, while the resource in Foveaux Strait adjacent to Bluff is approximately 300 Wm^{-2}.

9 REFERENCES

BTW (1989). Wave climate report Western Foveaux Strait. Report prepared for Electricorp Production. Report Ref. 8645.

Burger M.F, Van Gelder P.H.A.J.M, Gardner F. (2005). Wave energy converter performance standard "a communication tool. 6th European Wave and Tidal Energy Conference, Glasgow.

Egbert, G.D., and S.Y. Erofeeva, (2002). Efficient inverse modeling of barotropic ocean tides, *J. Atmos. Oceanic Technol.*, **19**(2), 183-204.

Flather, R.A. (1976) A tidal model of the northwest European continental shelf. Memoires de la Societe Royale des Sciences de Liege 6 (10), 141-164

Goda, Y. (1970). Numerical experiments on wave statistics and spectral estimates. Report of the Port and Harbour Research Institute, **9**(3): 3-57.

Hagerman, G. and Polagye, B. (2006). Methodology for estimating tidal current energy resources and power production by tidal in-stream energy conversion (TISEC) devices. ERI North American Tidal In Stream Power Feasibility Demonstration Project.

Hagerman, G. and Bedard, R. (2003) E2I/EPRI Specification – Guidelines for Preliminary Estimation of Power Production by Offshore Wave Energy Conversion Devices. E2I/EPRI-WP-US-001, December 22, 2003

Heriot-Watt University, and The University of Edinburgh, (2007). Peliminary Wave Energy Device Performance Protocol. Supporting Commentary, Version 1.3. 30p

Holthuijsen, L.H., Booij, N., Ris, R.C., Haagsma, I.J.G., Kieftenburg, A.T.M.M., Kriezi, E.E., Zijlema, M. and van der Westhuysen, A.J. (2007) SWAN Cycle III version 40.51 User manual. Available: http://fluidmechanics.tudelft.nl/swan/index.htm

Komar, P. D. (1976). Boundary layer flow under steady unidirectional currents. Pp. 91–106 in *Marine Sediment Transport* and *Environmental Managements,* D.J. Stanley and D.J.P. Swift, eds. John Wiley, New York.

Marchesiello, P., Mc Williams, J.C. and Shchepetkin, A. (2001) Open boundary conditions for the long-term integration of regional oceanic models. Ocean Modelling, 3, 1-20

Mellor, G.L. (2004) Users guide for “A three-dimensional, primitive equation, numerical ocean model”. Princeton University, Princeton, NJ. Available from: http://www.aos.princeton.edu/WWPUBLIC/htdocs.pom/

Orlanski, I. (1976) A simple boundary condition for unbounded hyperbolic flows. Journal of Computational Physics 21, 251-269.

Polagye, B and Bedard, R., (2006). System Level Design, Performance, Cost and Economic Assessment – Minas Passage Nova Scotia Tidal In-Stream Power Plant.

Salter S.H. and Taylor J.R.M., (1984). Bending moments in long spines. Edinburgh University Wave Power Project report submitted to the UK Wave Energy Steering Committee.

Tolman, H.L. and D. Chalikov, (1996). Source terms in a third-generation wind-wave model. *J. Phys. Oceanogr*, 26, 2497-2518.